TELEROBOTIC ON-ORBIT REMOTE FLUID RESUPPLY SYSTEM

FINAL REPORT

September 17, 1990

PREPARED FOR

Mr. Thomas C. Bryan
Information & Electronics Systems Laboratory
Guidance Control and Optical Systems Division
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

CONTRACT NO.: NAS8-37743

Approved by: Jay H. Laue
Jay H. Laue
Director
Aerospace Systems Directorate

Approved by: Charles W Mead
C. W. Mead
Senior Vice President
General Manager

SRS TECHNOLOGIES

SYSTEMS TECHNOLOGY DIVISION

990 EXPLORER BLVD. N.W.
CUMMINGS RESEARCH PARK WEST
HUNTSVILLE, ALABAMA 35806

(205) 895-7000

FOREWORD

This final report was prepared by SRS Technologies under Contract No. NAS8-37743, entitled "Telerobotic On-Orbit Remote Fluid Resupply System", for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Information and Electronics Systems Laboratory Guidance Control and Optical Systems Division with Ms. Pamela Nelson as Project Manager.

This report describes the work performed on the subject contract, during the May 1989 - July 1989 period by the Aerospace Systems Directorate in the SRS Systems Technology Group. The key project personnel included:

SRS Technologies	SPARTA Inc.	United Applied Technologies
John D. Carroll	Richard Matthews	Rodney Bradford
Joseph C. Cody		Larry Bradford
Paul A. Gierow		
Jim Morrison.		

CONTENTS

CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

This final report describes the development of a telerobotic on-orbit fluid resupply demonstration system, performed under contract NAS8-37743. The primary objective of this contract was to provide a fluid transfer demonstration system which would functionally simulate operations required to remotely transfer fluids (liquids or gases) from a servicing spacecraft to a receiving spacecraft through the use of telerobotic manipulations. The fluid system is representative of systems used by current or planned spacecraft and propulsion stages requiring on-orbit remote resupply. The system was integrated with an existing MSFC remotely controlled manipulator arm to mate/demate couplings for demonstration and evaluation of a complete remotely operated fluid transfer system. The fluid transfer system that was delivered to MSFC is shown in Figure 1.0-1.

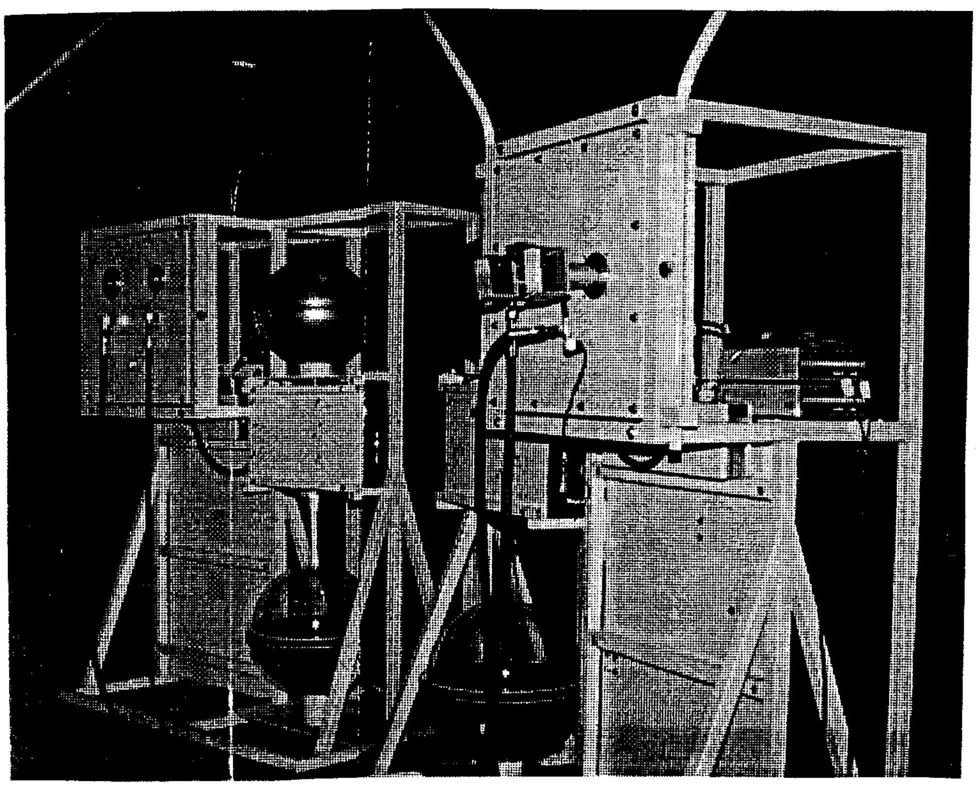


Figure 1.0-1. Fluid Transfer System

This fluid transfer system has the ability to measure and record forces and moments imparted to both servicing and receiving interfaces by the Protoflight Manipulator Arm (PFMA) during the conduction of remote servicing operations. The location of the PFMA end effector can be determined and recorded for all transfer operations to establish an operating envelope for the arm. Operator skills can be evaluated based on time required to accomplish tasks, minimum loads generated, the operational envelope required, and the minimizing of operational errors. This data can be used to evaluate the capability of a telerobotic system in the performance of typical tasks required for on-orbit fluid transfer.

The objective of this effort was accomplished through the performance of the technical approach, depicted in Figure 1.0-2.

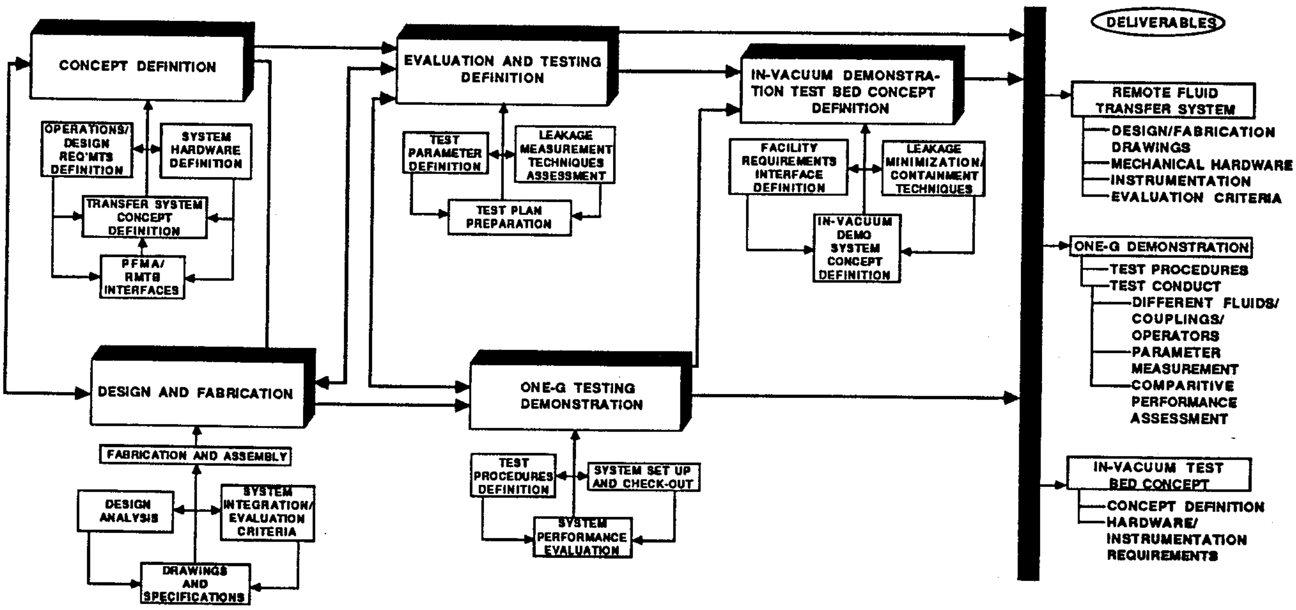


Figure 1.0-2. Telerobotic On-Orbit Remote Fluid Resupply System Task Flow

2.0 FLUID TRANSFER SYSTEM DEFINITION

The following sections describe requirements that governed the operation, design and concept definition of the Telerobotic On-Orbit Remote Fluid Transfer Demonstration System. Information regarding space fluid transfer, PFMA test bed capabilities and constraints, and data acquisition and control requirements were synthesized in order to define the fluid transfer system's baseline requirements. These baseline requirements were used to develop analytical computer models for forming the system concept definition and performing analysis of system hardware.

2.1 Operation and Design Requirements

The fluid system is representative of actual systems used by current or planned spacecraft and space-based propulsion systems and utilizes the existing PFMA/Remote Manipulator Test Bed (RMTB) at MSFC for demonstrating mating and demating of some specially designed fluid coupling end effector tools. The system incorporates a means for PFMA operational task performance evaluation through the measurement of forces and moments imparted on the instrumented task panel by the PFMA and the tracking of the PFMA's end effector tool used, during fluid transfer operations. The objectives were accomplished by defining and evaluating fluid servicing requirements, defining and specifying fluid system hardware requirements consistent with PFMA capabilities, and providing specifications, operations and data requirements to completely define a fluid transfer demonstration system. The information was used to fully characterize viable on-orbit fluid transfer systems to provide an understanding and data base for concept definition of a ground-based remotely operated fluid transfer demonstration. Although primary emphasis was placed on characterizing remotely operated systems, those planned for manned operation were evaluated for their potential application to remote operations.

2.1.1 Space Fluid Transfer Requirements and Operations

With the recent identification of Space Station Area Traffic Control restrictions, the importance of Orbital Maneuvering Vehicle (OMV) and Orbit Transfer Vehicle (OTV) operations has greatly increased. Remote fluid resupply operations in conjunction with these telerobotic space vehicles will be numerous. In addition to the fluids resupply requirements, the OMV, OTV, and other upper stage propellant requirements alone show the criticality of this technology in the future. Shown in Figure 2.1-1 is a summary of fluid storage/transfer requirements and accommodations needed to satisfy the fluid replenishment requirements of potential stages and spacecraft.

The OMV requirements for fuel and pressurant storage dictates the need for a fluid storage depot on the Space Station. To minimize risk, a requirement exists to fully automate the process with robotic or teleoperated umbilical quick disconnects for fluid transfer operations. Similar requirements for the OTV supports the need for a cryogenic storage and transfer facility.

Scheduled retrieval of satellites from operational orbits and their return to the Space Station for resupply of expendables including propellants, pressurants, and instrument cooling fluids also drives the Space Station requirement for fluid storage and transfer capabilities.

REQUIREMENTS	STATION ACCOMMODATIONS
Orbital Maneuvering Vehicle	
• DELIVER BI-PROPELLANT (MMH-NTO), PRESSURANT (He),AND COLD GAS (N_2) TO SPACE STATION • FACILITY STORAGE AND TRANSFER • FLUID TRANSFER TO OMV, MEASURE MASS TRANSFERRED,RESIDUALS • MONITOR/CONTROL LEAKAGE • OPERATIONAL SAFETY	• BERTHING OF OTV AT DEPOT • FLUID DEPOT TO STORE/TRANSFER PROPELLANTS,PRESSURANTS,AND COLD GAS • AUTOMATED,ROBOTIC ARM,QUICK CONNECT/DISCONNECT FOR TRANSFER OPERATIONS • LEAK DETECTION AND CONTROL • VENT GAS RECLAIMATION AND CONTROL • CLEAN UP EQUIPMENT
Orbit Transfer Vehicle	
• DELIVER CRYOGENS,PRESSURANTS • FACILITY STORAGE AND TRANSFER • FLUID TRANSFER TO OTV,MEASURE MASS TRANSFERRED,RESIDUALS • MONITOR/CONTROL LEAKAGE • OPERATIONAL SAFETY	• BERTHING OTV AT DEPOT • FLUID DEPOT TO STORE/TRANSFER CYROGENICS AND PRESSURANTS • AUTOMATED ROBOTIC ARM,AUTOMATED CHILL DOWN OF RECEIVER TANK, FLUID TRANSFER QUICK CONNECT/DISCONNECT • VENT GAS RECOVERY AND CONTROL • LEAK DETECTION AND CONTROL • CLEAN UP EQUIPMENT
Satellite/Spacecraft	
• DELIVER STORE PROPELLANTS, PRESSURANTS,INSTRUMENT FLUIDS • TRANSFER TO VEHICLES,MEASURE AMOUNTS DELIVERED AND RESIDUALS • CONTROL AND MONITOR LEAKAGE • OPERATIONAL SAFETY	• BERTHING AT DEPOT • SPACECRAFT PROPELLANT,PRESSURANT INSTRUMENT FLUIDS STORAGE/RESUPPLY FOR REPLACEMENT OF SPACECRAFT FLUIDS • FLUID TRANSFER INTERFACE MECHANISMS ROBOTIC ARM • VENT GAS RECOVERY/CONTROL • LEAK DETECTION/CONTROL

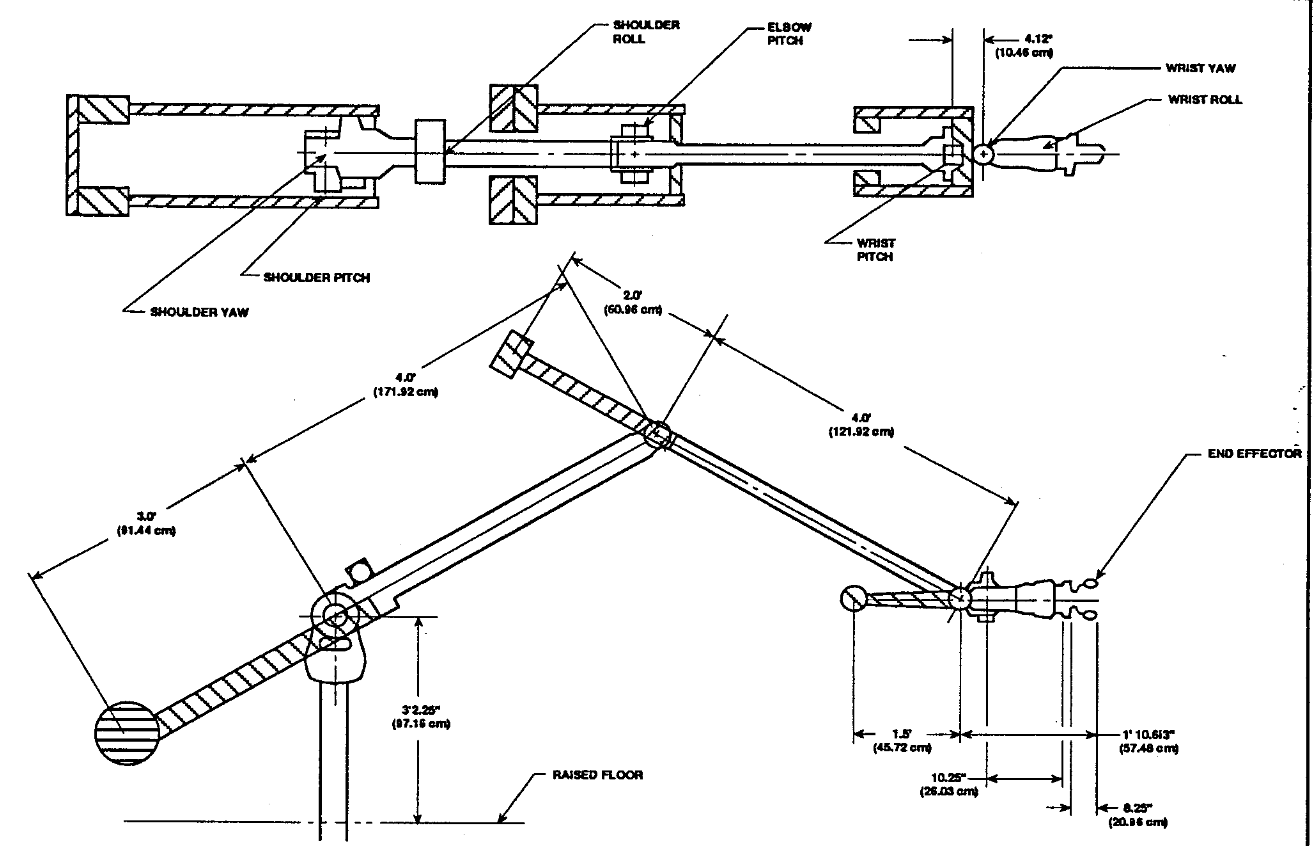
Figure 2.1-1. Fluid Storage/Transfer Requirements and Accommodations

The OMV requirements for fuel and pressurants dictate the need for a storage depot. Due to the hazardous nature of the propellants, a fully automated process with robotic or teleoperated devices with quick connect/disconnect fluid couplings is highly desirable. Measurement and display capabilities are required to determine the amounts of fluid transferred and the residuals remaining. Due to the toxic and corrosive nature of storable propellants, leakage must be essentially nonexistent and monitoring equipment must be used to assure no leakage or contamination occurs during storage or transfer operations. In addition to the automated transfer, monitoring equipment is required for visual observation.

Although OTV fueling requirements mandate similar cryogen storage and transfer needs, there are significant differences in hardware and operational requirements. For example, transfer of bipropellants can be done with ullage control utilizing small bladders in the transfer tanks. Transfer of cryogenics in zero-g requires the use of surface tension devices to ensure liquid is at the transfer pump inlet and vapor is at the receiver tank vent.

2.1.2 PFMA/Remote Manipulator Test Bed Capabilities and Constraints

The capabilities and constraints of the PFMA were analyzed to ensure that fluid transfer concepts derived are compatible with its capabilities. The PFMA is a single arm, robotic with seven degrees of freedom. This device is an up-rated derivative of the Integrated Orbital Servicing System and has a greater kinematic range capability and an additional degree of freedom. The PFMA's design was optimized for radial and axial servicing tasks. A schematic of the PFMA and a listing of its major capabilities/constants are shown in Figure 2.1.2-1.



PFMA DEPLOYED CONFIGURATION

COUNTERBALANCES FOR GROUND USE

MAXIMUM TORQUE RESISTANCE OF WRIST ROLL ASSEMBLY: 25-30 ft-lbs
MAXIMUM LIFT WEIGHT: 10 lbs[1]
MAXIMUM SQUEEZE FORCE OF JAWS: 35-40 lbs[2]
WIDTH OF JAWS: 3.25 inches
ELECTRICAL CONNECTOR: FEMALE CONNECTOR FOR SELF ALIGNING PROBE-TYPE MALE
SHOULDER PITCH: 180-200° (±90-100 from vertical)
ELBOW PITCH: 283° (±110, -173 from straight)
WRIST PITCH: 180° (±90 from straight)
SHOULDER YAW: 400° (±200° from forward)

WRIST YAW: 180° (± from horizontal)
WRIST ROLL: CONTINUOUS
MAXIMUM EXTENDED REACH: 9.9 feet [3]
NOTES:
(1) FOR PFMA/IEE CONFIGURATION ITB WEIGHT MUST BE SUBTRACTED FROM 10 lbs (AS WELL AS TOOL AND PAYLOAD)
(2) MAY BE INCREASED TO 100 lbs
(3) FROM VERTICAL CENTERLINE OF SHOULDER TO TIP OF IEE

TORQUE FOR EACH JOINT OF THE PFMA

JOINT	AVERAGE TIP FORCE (lb.)	TORQUE (ft-lb.)
SHOULDER YAW	12.50	120.50
SHOULDER PITCH	12.25	118.10
ELBOW PITCH	11.00	62.00
WRIST PITCH	9.00	14.70
WRIST YAW	14.00	18.10
WRIST ROLL	10.50	8.70

SCALE FACTORS FOR THE RATE OF EACH JOINT OF THE PFMA

JOINT	SCALE FACTOR AT +1.00 V INPUT (°/sec/volt)	SCALE FACTER AT -1.00 V INPUT (°/sec/volt)
SHOULDER PITCH	2.034	-1.934
SHOULDER YAW	1.510	-1.280
ELBOW PITCH	-2.660	2.334
WRIST PITCH	-10.000	11.660
WRIST YAW	2.850	-2.500
WRIST ROLL	1.278	-1.306

890120JohnC1120

Figure 2.1.2-1 PFMA Characteristics

ORIGINAL PAGE IS OF POOR QUALITY

2.1.3 Electronic and Electromechanical System Requirements

In order to evaluate the capability of the telerobotic system in the performance of the typical tasks required for on-orbit fluid transfer, the fluid transfer system incorporates various sensors and a data acquisition and control system. The electronic/electromechanical system was required to include a three-dimensional target tracking system, a three-dimensional force and moment measuring system, and required electronic and electromechanical equipment needed to monitor and control fluid flow throughout the system.

The three-dimensional target tracking system is used to define the location of the PFMA end effector in reference to a chosen origin. The three-dimensional force and moment measuring system was required in order to determine the forces and moments imparted on the instrumented task boards in which the fluid transfer connectors are mounted, during telerobotic fluid transfer operations. Actual fluid system tank pressures, transfer rates, transfer times, etc. were evaluated to estimate the required line sizes, stiffness, lengths, and tanks size/configuration for the fluid transfer system. Flow rates for the demonstration transfer system are within the flow/pressure loss capability of the fluid connectors used.

2.2 Fluid Transfer System Concept Definition

This task provided the analysis, design, and systems integration required to develop a concept definition for a remotely operated fluid transfer system demonstration in one-g. The basic components and subsystems were defined to provide a viable representation/simulation of a fluid transfer operation representative of planned propulsion and/or spacecraft on-orbit remote fluid transfer systems. The results of synthesis and evaluation of requirements and actual system hardware characterization were utilized in the definition of system design, operations, test, and data requirements. PFMA/RMTB capabilities and constraints were applied in the concept definition to assure compatibility with the fluid system definition, available end effectors, and connectors.

In order to eliminate the hazards of transferal of actual propellants and gases used for powering satellites and various other orbiting vehicles, water was selected as the best representative fluid for liquid propellant and air was selected as best candidate for the gas pressurant. Also, a measurement system for determining the three-dimensional forces placed on the test article and the three-dimensional position of the PFMA end effector relative to the test article was defined.

The fluid transfer demonstrator is configured to simulate typical servicing and receiving spacecraft fluid systems. The system consists of a supply station and a receiver station as shown by an earlier artist conceptual drawing in Figure 2.2-1.

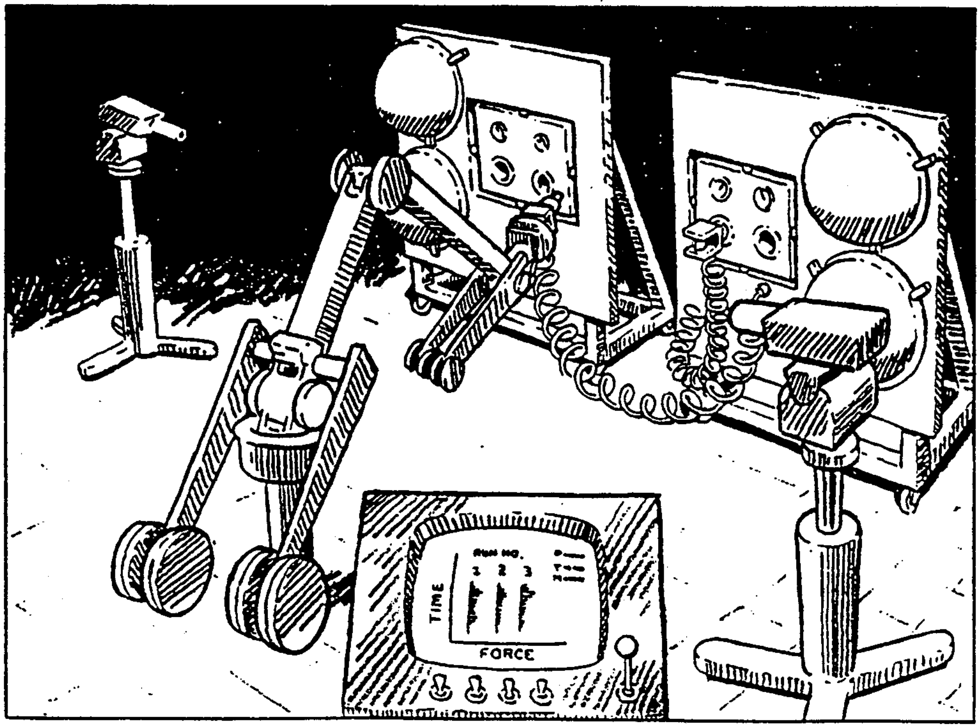
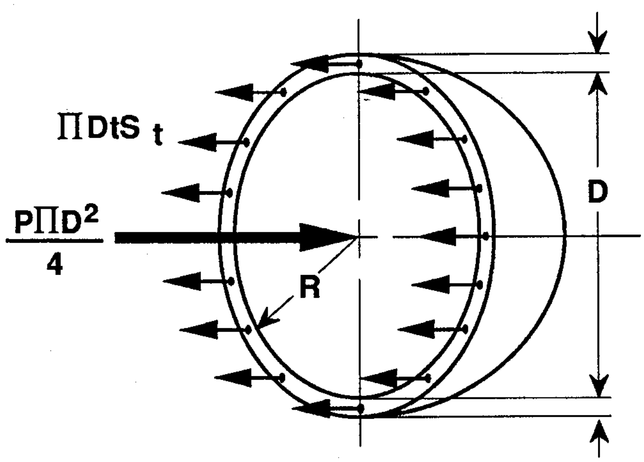


Figure 2.2-1. Fluid Transfer System Conceptual Definition

2.2.1 Liquid Spherical Tank Concept and Stress Analysis

In order for the fluid transfer demonstration system to be representative of the actual system used by current or planned spacecraft and space-based fluid transfer systems, spherical tanks utilizing bladders were chosen to be used as the system's liquid storage vessels. These tanks consisted of two thermoformed hemispherical sections mounted together by flanges located around the base of each section. A section of the fluid transfer sphere, as shown in Figure 2.2.1-1, shows the parameters of the static pressure equilibrium analysis. This general hemispherical section was analyzed in order to define the parameters governing the design of the transparent spherical liquid tank used in the fluid transfer system.



$$\frac{P\Pi D^2}{4} = \Pi D t S_t$$

where: P = Pressure (lbs/in^2)
D = Internal diameter of sphere (in)
t = Material thickness (in)
S_t = Allowable stress (lbs/in^2)

Figure 2.2.1-1. Hemispherical Section of a Spherical Liquid Tank

The material selected for fluid spheres was clear acrylic because of its transparent property, for viewing fluid transfer operations, and its good mechanical properties. The spheres were thermoformed in two halves with mating flanges. The mechanical properties of acrylics are high for relatively short-term loading. High stresses can be sustained safely for short periods, since the relatively low modulus causes a redistribution of stresses. For long-term service, however, tensile stresses must be limited to avoid crazing or surface cracking.

The computational analysis was based upon a stress level that would insure a factor-of-safety (FS) of 2. With this FS the material thickness (t) could be sized for operating pressure levels (P). Design pressure of 10 to 15 psi was specified for the water tanks. A fluid storage of approximately 5 gallons of water was chosen as the capacity of the storage sphere, to provide one minutes of transfer time at 5 gal/min. In order to determine the required diameter and wall thickness, the following equation for the volume of a sphere was used.

$$V = \frac{3}{4}\Pi R^3 = 1155 \text{ in}^3 \qquad \text{where: } V = (5 \text{ gallons}) \left(\frac{231 \text{ in}^3}{\text{gallon}}\right)$$

From this equation, the radius of the sphere (R) is 7.9 inches and the diameter (D) of the sphere is 15.8 inches. A 16 inch diameter spherical tank was chosen for the design due to its availability. Therefore, with a 16 inch diameter spherical acrylic tank and the allowable stress (St) set at 600 psi (1500/2.5 [where FS = 2.5]), the wall thickness (t) was calculated from the equation for static equilibrium, shown in Figure 2.2.1-1, and found to be 0.333 inches.

2.2.2 System Flow and Pressure Analyses for Conceptual Designs

The following analyses provided estimates of transfer flow rates and operating pressures for the air and water tanks used in the fluid transfer demonstration system. Pressure (flow) regulators are provided in the lines between the storage and transfer tanks. These pressure regulators allow the flow and transfer times to be adjusted to the required settings. Flow analyses provide upper values for operating pressures, and estimates of line pressure losses to assure that the system will provide a sufficient flow range. The actual transfer time can be adjusted with the pressure regulator.

The Purolator fluid connector used has a liquid (water) transfer rate of 5 gallons/minute, which is considered sufficient for a demonstration of fluid transfer. The coupling is sized for a nominal 1/2 inch fluid line. The fluid transfer line from the fluid supply tank to the fluid receiver tank is a flexible hose assembly 25 ft. in length with pipe threaded end fittings. The hose is a general purpose type, rated at 250 psi working pressure and 1000 psi minimum burst pressure. The hose has a nominal inside diameter of 1/2 inch and an outside diameter of 3/4 inch. The hose has an inner tube of neoprene, a fiber band over this, and a cover of neoprene overall. Weight of the hose is 13 lbs per 100 ft. Hose ends are brass, straight pipe threads (1/2 - 14) with a fluid passage opening of 0.391 inches.

According to manufacturer's literature, for a 25 ft. length of this hose, at a flow rate of 6 gpm of water, the pressure loss is 8.75 psi. The flow circuit between the fluid supply and storage tank contains a Purolator connector, hose, and four solenoid valves. The solenoid valve pressure losses are assumed to be 0.2 velocity head each. The liquid transfer system K factor is calculated as shown below.

$$K = \frac{\Delta P}{\rho V^2/2g} = \frac{\Delta P}{\frac{1}{\rho}\left(\frac{\omega}{A}\right)^2 A}$$

The total K factor was calculated as follows:

$$K = \left[K_e + K_v + K_p \left(\frac{Ae}{Ap}\right)^2\right] = \left[13.78 + 1.2 + (3.42)\left(\frac{0.5}{0.39}\right)^2\right] = 20.6$$

where: K_e is the K factor for the hose
K_v is the K factor for the valves
K_p is the K factor for the Purolator connector

By solving the initial equation for ω and substituting in the total K factor, a plot of the flow rate verse the difference in pressure was developed and is shown the Figure 2.2.2-1.

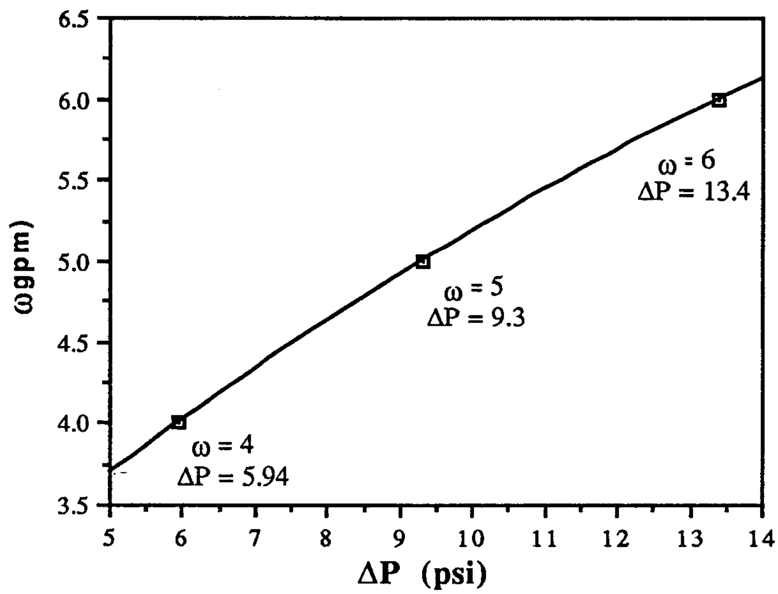


Figure 2.2.2-1 System Flow Rate vs. Difference in Pressure

By regulating the supply pressure to the liquid storage tank to approximately 9.5 psig, a flow between the two tanks of 5 gpm can be provided. To assure ample margin for the regulator, the tank was designed for a working pressure of 50 psi.

The initial pressure required for the air supply tank is estimated as follows:

$$P_i V_a \quad = \quad P_f \,(V_a + V_f)$$

where: P_i = initial tank pressure
P_f = final pressure in both gas and liquid tanks = 24.5
V_a = volume of air tank = .47 ft^3 (dia. = 14 in.)
V_t = volume of liquid tank = .70 ft^3 (dia. = 16 in.)

Solving for P_i:

$$P_i = \frac{24.5}{.47}\,(.47 + .70) = 60.98 \text{ psia} = 46.28 \text{ psig}$$

The working pressure for the gas storage tank was set at 90 psi. Since the volumetric flow rate of air (Q_a) into the liquid storage tank equals the volume flow of water out of the tank, then:

$$Q_a = \frac{5 \times 8.34}{62.2} = .67 \text{ ft}^3/\text{min}$$

Since there is a shut off valve and pressure regulator in the three feet long 1/4" line between the air and water tanks, the air flow velocity can be determined as follows.

$$V = \frac{Qa}{A} = \frac{.67}{1.36 \times 10^{-3} \times 60} = 8.2 \text{ ft/sec}$$

From this value the Reynolds number was calculated to be:

$$R = \rho\,\frac{DV}{\mu} = \frac{(.1662)(.25/12)(8.2)(3600)}{.0429} = 2383$$

The flow is transitional, and the line pressure loss is estimated as:

$$\Delta p = f\frac{L}{D}\,\rho\frac{V^2}{2g}; \quad f = .04$$

$$\Delta p = \frac{(.04)(3)}{(.021)}\;\frac{(.1662)(8.2)^2}{(64.4)(144)} = 6.88 \times 10^{-3} \text{ psi}$$

Therefore, the gas side pressure loss for this small flow is negligible.

The gas transfer is made through the Fairchild Connector. With the supply gas bottle initially at 90 psia and the receiver gas bottle initially at 10 psia, the final bottle pressure will be approximately:

$$P_f = \frac{10 + 90}{2} = 50 \text{ psia} = 35.3 \text{ psig}$$

The pressure loss for a 25 feet, 1/4 inch inner diameter pipe was calculated to be 0.15 psi, and the additional pressure loss due to the Fairchild valve is small. Consequently a flow control valve in the line allows the flow to be set to the proper value to obtain a one minute transfer. Other transfer times can be obtained by adjusting these valves.

The preliminary design of the liquid tank is shown in Figure B-1, in Appendix B. This conceptual design was updated due to computer model analysis, as described later in the system design section, and limitation of available manufactured acrylic spherical tanks.

2.2.3 Concept for Remote Detection of Fluid Connector Leakage

Prior to initiating an on-orbit fluid transfer operation, it is necessary to verify that the fluid transfer connectors are capable of accommodating the transfer without excessive leakage. The concept for verifying the integrity of the remotely operational connectors is described in this section. The purpose of this system is to identify and quantify leaks that are large enough to preclude transfer operations. The purpose is not to verify specification leakage for the connectors. Leaks large enough to preclude transfer are dependent on the fluid to be transferred and the sensitivity of the surroundings to contamination or other undesirable effects. This system relies on the measurement of helium leakage and the correlation of this leakage to the leak rate of the fluid being transferred. Although the precise relation between helium and transfer fluid leakage must be determined by testing each connector, an approximation can be made using orifice flow correlations. Depending on the fluid being transferred, considerable helium may leak before appreciable transfer fluid leaks. The magnitude of helium leakage that signifies the inception of transfer fluid leakage was determined by testing each connector with helium and the candidate transfer fluid. The system described here is to provide a concept demonstration and is not intended to meet flight requirements specifically in the areas of single point failures, redundancy, etc.

Solenoid valves are used to isolate each connector to allow pressurization of the connectors with helium. The basic approach is to isolate a volume of helium and measure the pressure decay to determine the leakage rate. The volume to be isolated contains the connector, line and isolation values. This volume was determined by the actual measurement of each components volume. This approach relies on sealing all leak paths except the connector. In a flight system, redundant isolation valves would be employed to accommodate this, and to eliminate single point failures.

The fluid transfer demonstration system relies on the measurement of helium leakage and correlation of air and water leak rates with helium leakage. Assuming the leakage through the connector to be similar to that through an orifice, the mass flow can be related to mass density and the pressure loss through the orifice.

$$1)\ \dot{w} = k\sqrt{\rho_1(P_1 - P_2)}$$

where: ρ: fluid density
$\dot{w}$: mass flow rate
P: pressure where: (Subscripts 1 & 2 are upstream and downstream conditions.)
k: is dependent on the geometry of the leak and to a lesser extent the properties of the fluid.

Rearranging Equation 1,

$$2)\ P_1 - P_2 = \Delta P = \frac{\dot{w}^2}{K^2 \rho_1} = \frac{\rho_1 Q^2}{K^2}$$

Using Equation 2 for equivalent pressure loss and k values the volumetric leakage of air can be related to helium.

$$3)\ Q_a = \sqrt{\frac{\rho_{He}}{\rho_a}}\ Q_{He}$$

If both gases are at the same temperature and pressure:

$$4)\ Q_a = \sqrt{\frac{M_{He}}{M_a}}\ Q_{He}$$

where: M_{He} = Molecular weight of the helium = 4
M_a = Molecular weight of the air = 28.96

$$Q_a = \sqrt{\frac{4}{28.96}}\ Q_{He} = 0.372\ Q_{He}$$

Therefore, about three times more helium will leak through an opening than air at equivalent pressures and temperatures. Since water is an incompressible fluid, and helium is compressible, the compressibility effects are introduced as follows:

$$5)\ \dot{w}_{He} = K\, Y_{He} \sqrt{\rho_{He} (P_1 - P_2)}$$

$$\Delta P = \frac{\rho_{He}\, Q_{He}^2}{(K\, Y_{He})^2}$$

where: Y_{He} = Compressibility effect for Helium ≈ 0.8

For water, the change in pressure is

$$\Delta P = \frac{\rho_{H_2O}}{K^2}\, Q_{H_2O}^2$$

where the compressibility factor for water is 1.

The relation between water and helium leakage is:

$$7)\ Q_{H_2O} = \sqrt{\frac{\rho_{He}}{\rho_{H_2O}}}\ \frac{Q_{He}}{0.8}$$

For helium at 15 psia and 80°F

$$8)\ \rho_{He} = \frac{15 \times 144}{(386.33)(540)} = .01$$

The leakage rate of water compared to helium is therefore:

$$9)\ \dot{Q}_{H_2O} = \sqrt{\frac{.01}{62.2}}\ \frac{1}{0.8}\ Q_{He} = .0159\ Q_{He}$$

The helium leak is about 63 times as great as water for these conditions. This difference in the leakage rates allowed for finer adjustment and calibration of the leakage detection system.

The concept for leak checking the fluid transfer connectors is to pressurize the connector with low pressure helium in a known volume, monitor the pressure decay rate, and evaluate the information. Assuming the temperature is constant and the ideal gas law is applicable.

$$10)\ \dot{w} = \frac{V}{RT}\ \frac{dP}{dt}$$

where: P, T, V, and R are pressure, temperature, volume, and gas constant, respectively.

$$11)\ \dot{w} = \rho Q = \frac{P}{RT}\dot{Q}$$

$$12)\ \dot{Q} = \frac{V}{P}\ \frac{dP}{dt}$$

For a constant volumetric leak rate "Q" Equation 12 can be integrated, as shown below.

$$13)\ \dot{Q} = \frac{-V}{\Delta t}\ \ln \frac{P_f}{P_i}$$

The time required to monitor a given leak rate for a given pressure ratio is determined by:

$$14)\ \dot{Q} = -\frac{V}{\dot{Q}}\ \ln \frac{P_f}{P_i}$$

This shows that small volumes and large leaks give the largest pressure differences for a given time.

For a given leak rate of air or water, helium leaks considerably more. The use of helium gas has the advantage of reducing the time required for the pressure to decay for a reasonable pressure measurement. If helium were used with a volume of 3 in^3 and 10% change in pressure with an air leak of 10^{-3} ccs, the observation time would be as follows:

$$\Delta t = \frac{(4)\ (2.45)^3\ (.372)}{60 \times 10^{-3}} \ln (27/30) = 32.25 \text{ min}$$

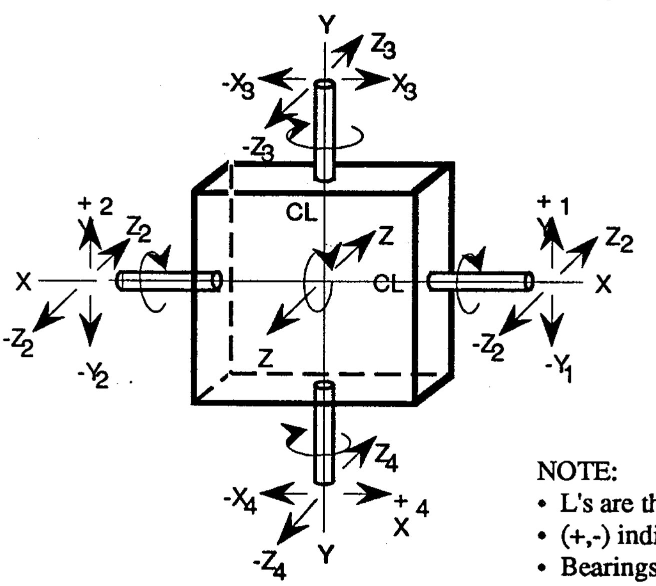
The same case for a water leak of 10^{-3} ccs would give

$$\Delta t = \frac{(3)\ (2.53)^3\ (.021)}{60 \times 10^{-3}} \ln (27/30) = 1.82 \text{ min}$$

Since the purpose of the remote leak detection system is to detect leaks large enough to preclude transfer of fluid, and not to verify spec.'s leakage, the time required to detect larger leaks with this design is considered acceptable.

2.2.4 Concept for PFMA Operator Evaluation System

In order to evaluate the PFMA operator, concepts were defined that allow the measurement of forces and moments during the mating/demating operations and determines the three-dimensional location of the PFMA end effector during fluid transfer operation. The forces are measured by mounting the connectors in a frame that is supported at four locations by cantilever force beams, allowing for all of the forces and moments applied to the connector to be measured. The torques and forces at any location on the test article can be determined from the measured values and displayed in real time and/or recorded as indicated. This conceptual three-dimensional force measurement system is shown on the following page in Figure 2.2.4-1. The resupply station is equipped with a three-dimensional target tracking system that allows the PFMA operator to know the precise coordinate or location of the PFMA end effector tool in reference to the task board. The three-dimensional information, can be determined by placing each two-dimensional position sensor equal distances from a chosen origin on perpendicular planes from each other the relative position of the PFMA end effector during the mating operation can be determined.



About X - X Axis

$\Sigma\ M_{CWX} = (F_{Z3})\ (L_3) + (-F_{Z4})\ (L_4)$

$\Sigma\ M_{CCWX} = (-F_{Z3})\ (L_3) + (F_{Z4})\ (L_4)$

About Y - Y Axis

$\Sigma\ M_{CWY} = (F_{Z3})\ (L) + (-F_{Z1})\ (L)$

$\Sigma\ M_{CCWY} = (F_{Z1})\ (L) + (-F_{Z2})\ (L)$

About Z - Z Axis

$\Sigma\ M_{CWZ} = L\ [(F_{X3}) + (-F_{X4}) + (F_{Y2}) + (-F_{Y1})]$

$\Sigma\ M_{CCWZ} = L\ [(-F_{X3}) + (F_{X4}) + (-F_{Y2}) + (F_{Y1})]$

NOTE:
- L's are the length along the center line from the origin = constant
- (+,-) indicates sensor voltage output from strain gauge network
- Bearings about shafts X-X & Y-Y prevent axial shaft loading

Figure 2.2.4-1 Conceptual Force Measurement System

3.0 FLUID TRANSFER SYSTEM DESIGN

The fluid transfer demonstrator is configured to simulate typical servicing and receiving of spacecraft fluid systems. The system consists basically of two identical stations: a supply station and a receiver station. Liquid or gas is transferred from supply to receiver station. In the reverse mode, the liquid may be transferred bi-directionally from the receiver to the supply tank by pressurizing the gas receiver tank and valving off the gas supply tank. To facilitate the flow, the Purolator coupling is used for liquid transfer and the Fairchild connector is used for gas transfer. Each station will facilitate operation of the coupling (mate/demate) from a square task panel. The supply station is provided with a Purolator and a Fairchild storage receptacle for storing the male halves of the coupling devices. The receiver station is provided with both female halves of each coupling. Both the supply and receiver panels are instrumented to measure forces and torques exerted upon the panel by the PFMA, through the application of "joy stick" type strain gauge instrumented beams. These instrumented beams provide an analog output, measuring forces in the X, Y, Z axis of the panel. Also, a measurement system for determining the three-dimensional position of the PFMA end effector relative to the test article was designed.

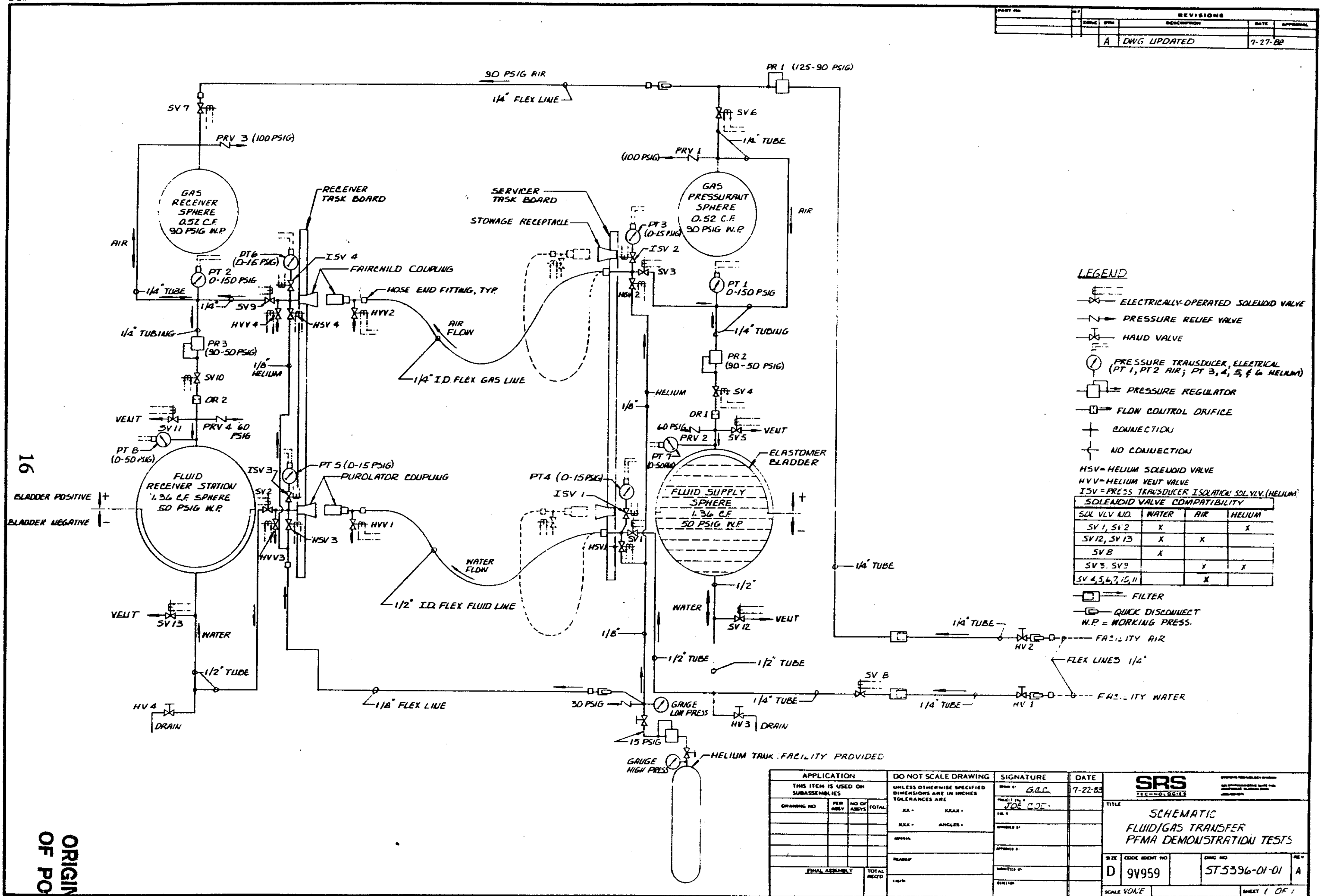
3.1 Fluid Transfer Demonstration System Hardware

The basic items of hardware at each station are a spherical liquid tank, a spherical gas pressurant tank, an instrumented task panel with coupling storage (or receptacle) devices attached, flexible fluid and gas transfer lines, and system valves. To provide portability, each station consist of a structural framework with a soft-mount cradle to support the pressurant and fluid tanks. The liquid and gas couplings are mounted on a task panel with an outer and inner frame to facilitate the "joy stick" force sensors, and an A-frame type structure.

The schematic of the gas and liquid flow circuit for the fluid transfer demonstration system is shown in Figure 3.1-1. This system provides for the simulation of transfer of both gas and liquid. A capability for remote leak checking of the fluid connectors in both the demated and mated configurations is provided. The liquid lines can be remotely purged of liquid after liquid transfer and prior to storage of the servicer half on the fluid connector.

3.1.1 Structural Framework

The fluid transfer system consists of two free-standing support frameworks, one frame for the servicer task panel (supply side) and one frame for the receiver task panel (resupply side). The frameworks are identical in dimensions, but are of opposite hand orientation. Figure B-2, in Appendix B, is a mechanical assembly drawing (Drawing No. ST5396-01) defining the frame at the receiver task panel. The structural framework consists of a 1.50 inch square tubular framework of steel, welded construction, with two valve panels and one electronic equipment mounting panel bolted to the frame. Not shown on this drawing is the structural cradle support for



16

Figure 3.1-1. Final Fluid Transfer Demonstration System Schematic

ORIGINAL PAGE OF POOR QUALITY

the gas and fluid spheres. Flexible fluid, gas and helium lines interface the two systems through either liquid/gas couplings or via quick-disconnects such that each system framework is independent for portability. Each frame assembly has independent main valve panel assemblies consisting of pressure regulators, pressure relief valves, pressure transducers, solenoid control valves, hand valves and quick-disconnect coupling for fluid, gas, and helium supply sources. The valve sub-panels are located in close proximity of their respective task panel to facilitate the helium leak check operation.

The receiver task panel is the standard inner and outer frame assemblies with strain gauge joy-stick load sensors, such as provided previously under contract NAS8-3607, Modification 9, and described in section 3.2.2. The receiver panel, mounted to the inner frame of the task panel assembly, contains the Purolator and Fairchild female coupling tool, while the servicer task panel (same configuration as the receiver task panel) has mounted storage receptacles for both couplers. To determine the force exerted upon the servicer task panel by the fluid and gas transfer lines, a bulkhead connector for each line (gas and fluid) was installed on the panel center lines to facilitate the interface fluid lines connection between the two stations. Storage receptacles are located immediately above the bulkhead connectors. These instrumented task panel connections for the supply side are shown in Figure B-3 (Drawing No. ST5396-01-02), in Appendix B.

3.1.2 Liquid Supply and Receiver Spheres

The PFMA fluid transfer system being designed for MSFC contains a clear acrylic thermoplastic sphere used to hold water with a working pressure of 10 psig. The sphere is made in two halves and joined with a bolted flange. An elastomer bladder is held in place by the clamping force between the two halves of the fluid sphere. The sphere has a hole on the top for the pressurant access and the bottom to allow the transfer water.

The design of the fluid sphere is described in more detail in Figure B-4 (Drawing No. ST5396-001B, page 1 & 2). This drawing of the acrylic sphere was investigated by computer aided stress modeling. This design effort was deemed necessary to eliminate inboard loading and distortion of the sphere at the hemispherical mating flanges, introducing excessive loading that might be caused by the V-band coupler torque. This third design iteration eliminates the V-band tightening arrangement and substitutes bolted connections around the mating flanges. At the same time, the flanges were thickened and are sandwiched between metallic annular rings to provide good bearing surfaces for the through bolt connections as well as the acrylic substrate. The spheres were pressure tested to proof pressures ≥4 x operating pressure to verify their structural integrity prior to integration into the system.

It is to be noted that for a clear acrylic sphere of this size and pressure requirements, stress analysis is more complex because this rather flexible material does not behave like standard metallic pressure vessels, and true stress-strain relationships are unlike metallic materials. Due to the pressurization of the sphere, a stress analysis was needed to ensure that there were no principal stresses to exceed acceptable limits. The stress analysis was performed using the 1988 version of COSMIC/NASTRAN. To ensure that the fluid transfer tank would not be over pressurized, a pressure relief valve was installed and set to 15 psig.

The fluid sphere in the PFMA fluid transfer system was constructed from standard grade clear acrylic thermoplastic. The Rohm and Haas Plexiglass G acrylic was used as a baseline for modeling. Material properties for Plexiglass G were obtained form Reference 1 and are shown in Figure 3.1.2-1. Since the Plexiglass G acrylic is a relatively brittle material, the yield strength was estimated to be close to the ultimate strength. A safety factor of at least 2.0 was used on the ultimate strength.

Density	74.38 lb/ft^3
Tensile Strength, Break	10.5×10^3 psi
% Elongation, Break	4.9%
Tensile Modulus	4.5×10^5 psi
Flexural Strength, Yield	16.0×10^3 psi
Flexural Modulus	4.5×10^5 psi

Figure 3.1.2-1. Summary of Material Properties for Plexiglass G

Even though the mechanical properties for acrylics are relatively high for short term loading, Reference 2 reports that for long term loading the tensile stresses should be limited to 1,500 psi to avoid crazing or surface cracking. The fluid sphere in the PFMA fluid transfer system is subjected to short term loading of approximately five minutes per demonstration.

A NASTRAN model was built to simulate the loading conditions of the fluid sphere. Due to geometrical symmetry and symmetric loading, the entire sphere was modeled as a wedge shaped segment. Since there are 24 holes in the flange, a 15 degree angle wedge was modeled. Boundary conditions were imposed by restricting rotations about the axisymmetric axis. A solid element was used in modeling due to singularity problems with axisymmetric elements. Also, the solid element allows easier modeling around the bolt hole. Figure 3.1.2-2 shows the geometry of the whole model and shows the detail in the flange.

The loading of the model includes a uniform pressure along the inside of the sphere. To model the load from the bolts and load distribution ring, a uniformly distributed load was applied to the flange to resist the internal pressure. This is an approximation to the load actually applied by the 24 bolts and aluminum ring on the flange. The contact force between the two hemispheres was modeled by constraining the appropriated degrees of freedom for the grid points at the contact. Due to the large number of grid points and elements, only principal stresses with a

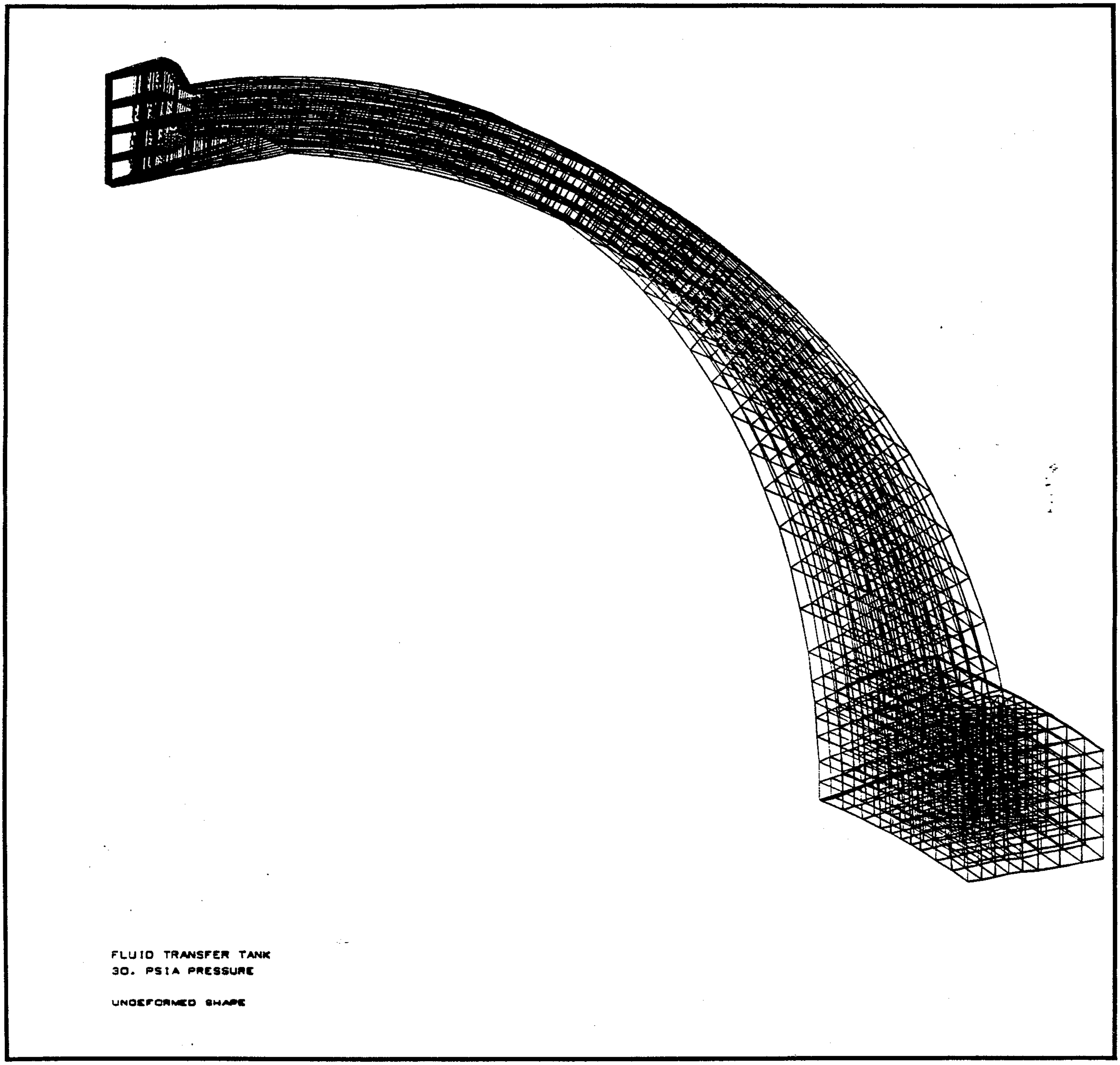


Figure 3.1.2-2. Geometrical Graph Representation of a Slice of the Fluid Sphere Model

magnitude greater than 1000 psi were used. This allowed a much easier analysis of the locations of stress concentrations.

The analysis of the fluid sphere is not as straight forward as it might seem because the equation for the stresses in a thin walled sphere do not hold true near the hole or flange. This equation is as follows:

$$s = Pr/(2t) \tag{1}$$

where: s = Principal Stress, r = Mean Radius, P = Pressure, t = Wall Thickness

The primary area of concern in the fluid sphere is the stress around the flange because the bending, shearing and normal forces on the flange produce the highest stresses in the fluid sphere. The stresses in the walls away from the flange or the hole are approximately equal to those calculated from equation (1). From this equation, the principal stresses in the wall away from the hole and flange are 255 psi for an internal pressure of 30 psi. For an internal pressure of 70 psi, the principal stresses in the walls rise to 595 psi. These stresses are well under the ultimate stress of 10,500 psi.

Because of the complex state of stress around the flange, a finite element model was used to predict the maximum principal stresses. For an internal pressure of 30 psi, the maximum principal stress estimated was 1718 psi. This stress would give a safety factor of 6.11. When the internal pressure was increased to 70 psi, the maximum estimated principal stress was 5194 psi. An internal pressure of 70 psi gives a minimum safety factor of 2.02. Since all principal stresses exceeded a safety factor of 2.0 and the safety factor at the normal operating pressure of 30 psi was 6.11, the fluid sphere meets safety requirements for the system.

Due to the manufacturing changes in the fluid transfer acrylic spheres, the stress analysis of the previous sphere configurations was updated. A new NASTRAN model was built based on actual dimensions taken from the manufactured spheres. The acrylic material is formed into the spherical shape by pressure and heat forming. The manufacturing process results in a sphere wherein the thickness lessens toward the center of the sphere. The details of the new model, shown in Figure 3.1.2-3, illustrates how symmetry and axisymmetry are both used to simplify the model.

As with the previous stress analysis, the maximum principal stresses are located around the sphere flange. These high stresses are a result of the bending, shear, and normal loads associated with the flange. A plot of the maximum principal stress versus internal pressure is shown in Figure 3.1.2-4. For an internal pressure of 10 psi the maximum principal stress is only -800 psi giving a safety factor of 13.1. The spheres were proofed to 40 psia which is four times the working pressure. The safety factor at proof is 2.5. The results of the analysis of the acrylic spheres yielded a safety factor greater than 2.0, which meets the safety requirements of the system.

The spheres received were assembled using steel flanges and stainless steel bolts. The inflatable bladder was attached to one of the hemispheres with silicone sealer and allowed to cure on

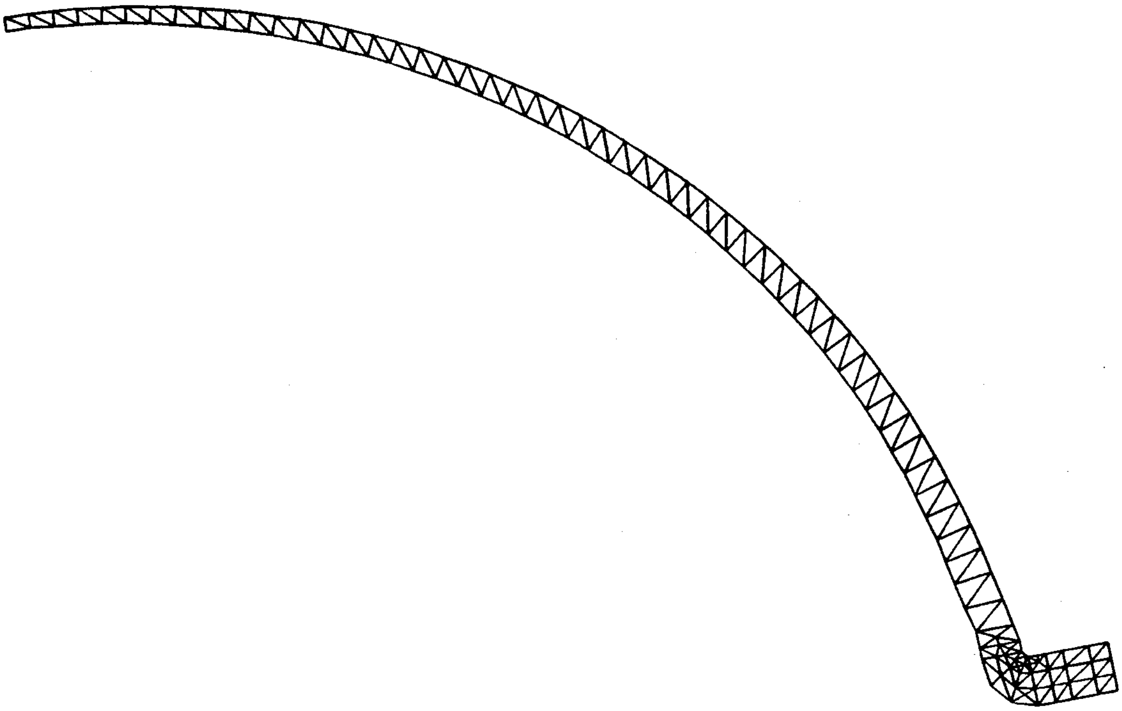


Figure 3.1.2-3. Cross-Section of NASTRAN Model

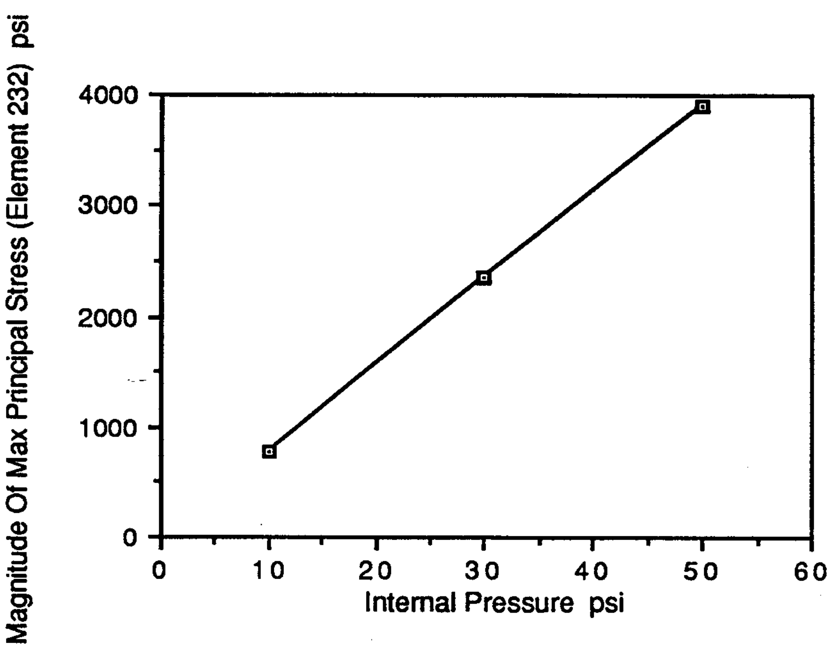


Figure 3.1.2-4. Stress vs. Internal Pressure

the sphere flange. Following a 24 hour cure time, the other hemisphere was mated to the bladder and first hemisphere with silicone sealer and stainless steel bolts, with the steel flanges mounted outside of the acrylic flanges. The spheres were pressure tested using water and a regulated air pressure. The spheres were initially filled with water and then the regulated air pressurant was applied to the sphere to provide for a more accurate pressure control. The pressurization procedure used for the tests are shown below.

1. Fill Tanks with Water
2. Close Water Valve
3. Pressurize to 20 psi with Air as Pressurant
4. Investigate Seals and Bladder for Leaks or Tears
5. Continue Pressurization at 0.5 psi/second until 40 psi is Reached
6. Hold at 40 psi for Three Minutes
7. Inspect for Leaks and Failure
8. Depressurize the Tank

Seven pressurization tests were performed as shown in Figure 3.1.2-5. Due to the extreme softness of the rubber used for the bladder, it extruded through the top of the sphere's 1/2 inch air outlet during one of the pressurization test. Although the sphere would not normally be subjected to the 35-40 psi pressure, which caused the bladder to extrude, a screen was place over the air outlet for subsequent pressurization tests. The screen design proved successful in eliminating the extrusion problem. Test #6 resulted in complete failure of the acrylic sphere at the flange. The failure was due to extremely low loads placed on the attachment screws. By performing the acrylic tank pressure tests, the optimum method for bolting the two half sphere together was developed. This was the method utilized for he tank used in test 7. The sphere tank pressurization tests were documented on video tape.

Test #	Date	Tank #	Proof Pressure	Test Results
1	5/17/89	PSP 1	55 psi	Meets proof pressure test (pretest, no bladder used)
2	5/19/89	PSP 2	35 psi	Bladder extruded thru top of tank (a screen was placed over the tank outlet on subsequent test)
3	5/22/89	PSP 3	40 psi	Meets proof pressure test
4	5/23/89	PSP 2	15 psi	Pin hole leak in bladder, test stopped
5	5/24/89	PSP 2	0 psi	Bladder extrusion thru side, not tested
6	5/26/89	PSP 2	40 psi	Failure of tank due to low torque loading on bolts
7	5/30/89	PSP 1	40 psi	Meets proof pressure test

Figure 3.1.2-5 Spherical Tank Pressure Test Results

3.1.3 Gas Supply and Receiver Spheres

The gas transfer spheres selected have a 14 inch diameter, pressurized to 90 psig internal pressure, storing about 0.81 cubic feet of gas (air). The gas sphere is a vendor-furnished item fabricated from 304 stainless steel with a wall thickness of 0.083 inch. The sphere has a port on one end with a one-quarter inch standard pipe threat that interfaces with the system tubing arrangement. The gas spheres have a pressure rating of 350 psig and were pressure tested and certified to this pressure at the factory. At 350 psig, a conservative safety factor of 4 x operating pressure can be expected. A copy of the certification is included in the appendix of this report.

3.2 Three-Dimensional Force Measuring System

The forces in the x, y, and z directions applied to the instrumented task boards, by the PFMA, are measured with strain gauges installed on beams mounted about the rectangular task board at its geometrical centers. Strain gauge signal conditioning and amplification circuits are used to monitor the instrumented joysticks at a rate of 10 Hz and produce information describing the strain placed on each beam in two directions. This strain data is converted into the three-dimensional force components that describe the forces imparted to the instrumented task board. Each joy stick produces a total of two force related signals, as shown in Figure 3.2-1. The corresponding force component signals are summed together in order to determine the total three-dimensional forces applied to the task board. The magnitude of the total force applied to the task board is calculated in order to give a general description of the forces applied by the PFMA to the instrumented task board.

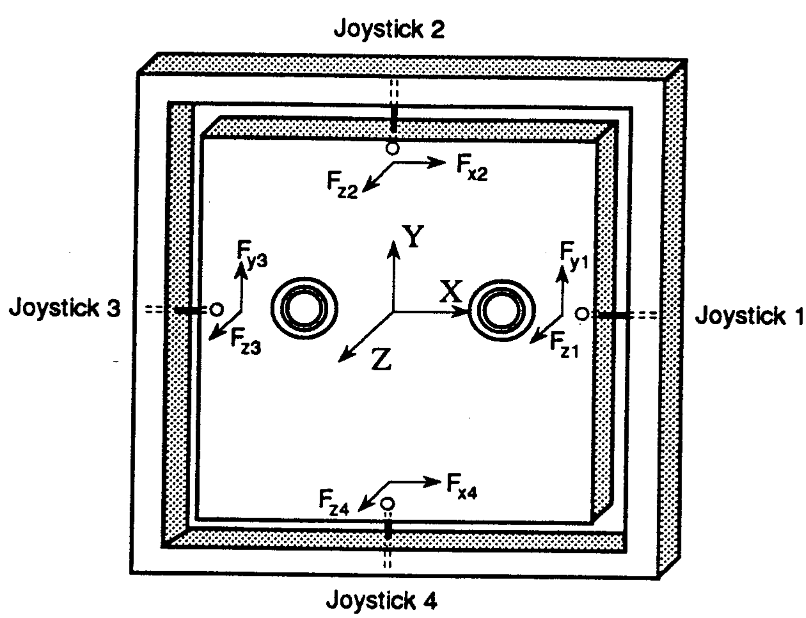


Figure 3.2-1. Instrumented Task Boards' Three-Dimensional Force Configuration

Converting the strain data into force data and the calculation of the three-dimensional force applied to the task board is accomplished through use of a LabVIEW control software. This data is stored and displayed on the computer monitor in real time graphic plots. This enables the controller's operations and actions to be monitored and evaluated.

3.2.1 Force Measurement System Hardware

In the remotely operated fluid transfer demonstration system, the supply and resupply stations each contain a square shaped instrumented task board supported by four force measuring joy stick assemblies. The basic design utilizes the load force beam ("joy stick") principle as the design baseline concept. The four beams are mounted on the vertical and horizontal axes of an internal rigid test frame that is supported by a separate rigid external frame mounted on a fixed support structure. With this arrangement, six degrees of movement of the internal frame can be monitored in units of pound forces applied to the frame by the PFMA. The operation of the force measuring cantilever beam assemblies is based upon the use of strain gauges, mounted 90° about the beam, to measure bending stresses in the beam due to the deflection of the beam. The design of the joy stick assemblies is shown in Figures 3.2.1-1. The detailed mechanical drawings of each part of the joystick is shown in Appendix B, Figures 5-10.

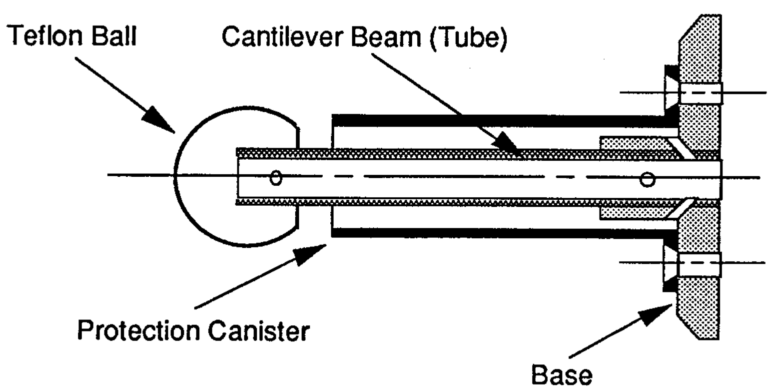


Figure 3.2.1-1. Instrument Task Board Joystick Mechanical Assembly

The external support frame, shown in Appendix B (Figure B-11), is a square shaped frame machined from a solid piece of aluminum to insure surface alignment. Figure B-11 also illustrates how the joysticks are attached to the external support frame. A thru hole is provided in each corner for mounting the frame to an alternate support structure. As with the external support frame, the internal support frame, as shown in Figure B-12, was machined from a solid piece of aluminum to insure surface alignment. The cross section of the inner frame was machined as an H-beam to reduce weight and maintain support. Located on the X-X axis and the Y-Y axis are precision bored holes to receive the ball ends of the joysticks.

3.2.2 Strain Gauge Signal Conditioning Circuit

The strain gauges are configured in a wheatstone bridge network with two active elements on half the bridge and two dummy resistors, located internally on the signal conditioning chip, completing the bridge. The strain gauges specified for the design are BLH gauge no. FAB-12-35-513-WL. These gauges have a nominal resistance of 350Ω to reduce the excitation current and the associated self heating. The signal conditioning chips selected are Analog Devices, model 1B31, which are hybrid strain gauge signal conditioning IC's. The strain gauge signal conditioning circuit design used for each joystick strain gauge pair is shown in Figure 3.2.2-1. The signal conditioners provide a precision excitation voltage for the strain gauges, filter and amplify the strain gauge signal, and supply a stable sensitive output which enable the measurement of very small forces acting on the fluid transfer system's instrumentation panels.

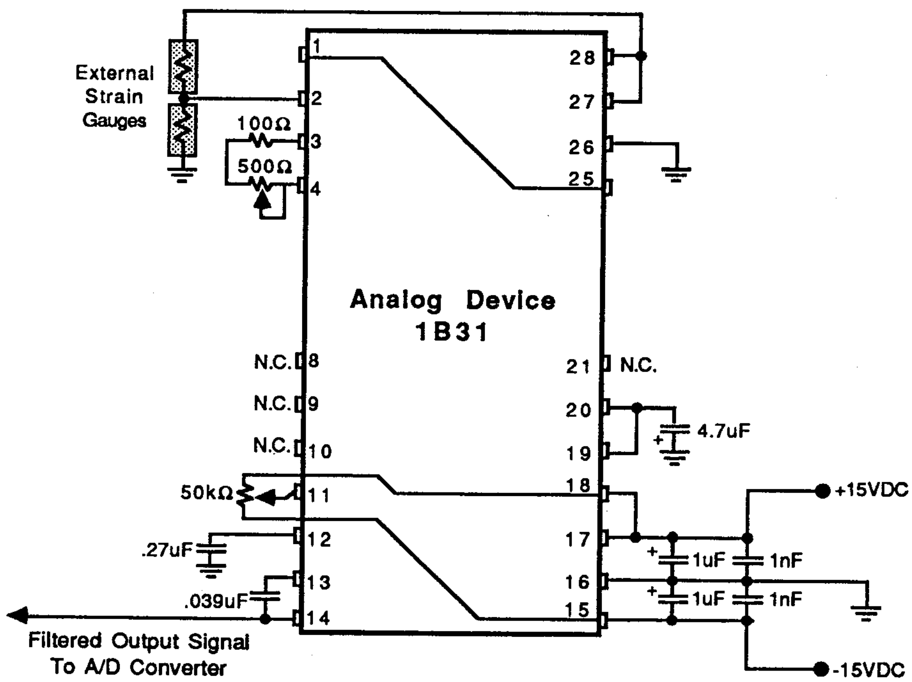


Figure 3.2.2-1 Strain Gauge Signal Conditioning Circuit

An electronic breadboard test of the strain gauge signal conditioning module was performed in the SRS electronic lab. A successful test was performed using a potentiometer to simulate the strain or change in resistance of the strain gauges. The breadboard test assured that the signal conditioners produce a noise-free amplified signal of the strain gauge output. Eight of the signal conditioning circuits were combined on one circuit board in order to control all strain gauges per instrumentation board. A printed circuit board (PCB) mask was designed in-house at SRS using an automated PCB design program (PC Board MacCAD) on a Macintosh II computer and printed on a laser printer. This one-sided PCB was fabricated with a top silk screen, as shown in Figure 3.2.2-2, 8 inches by 6 inches.

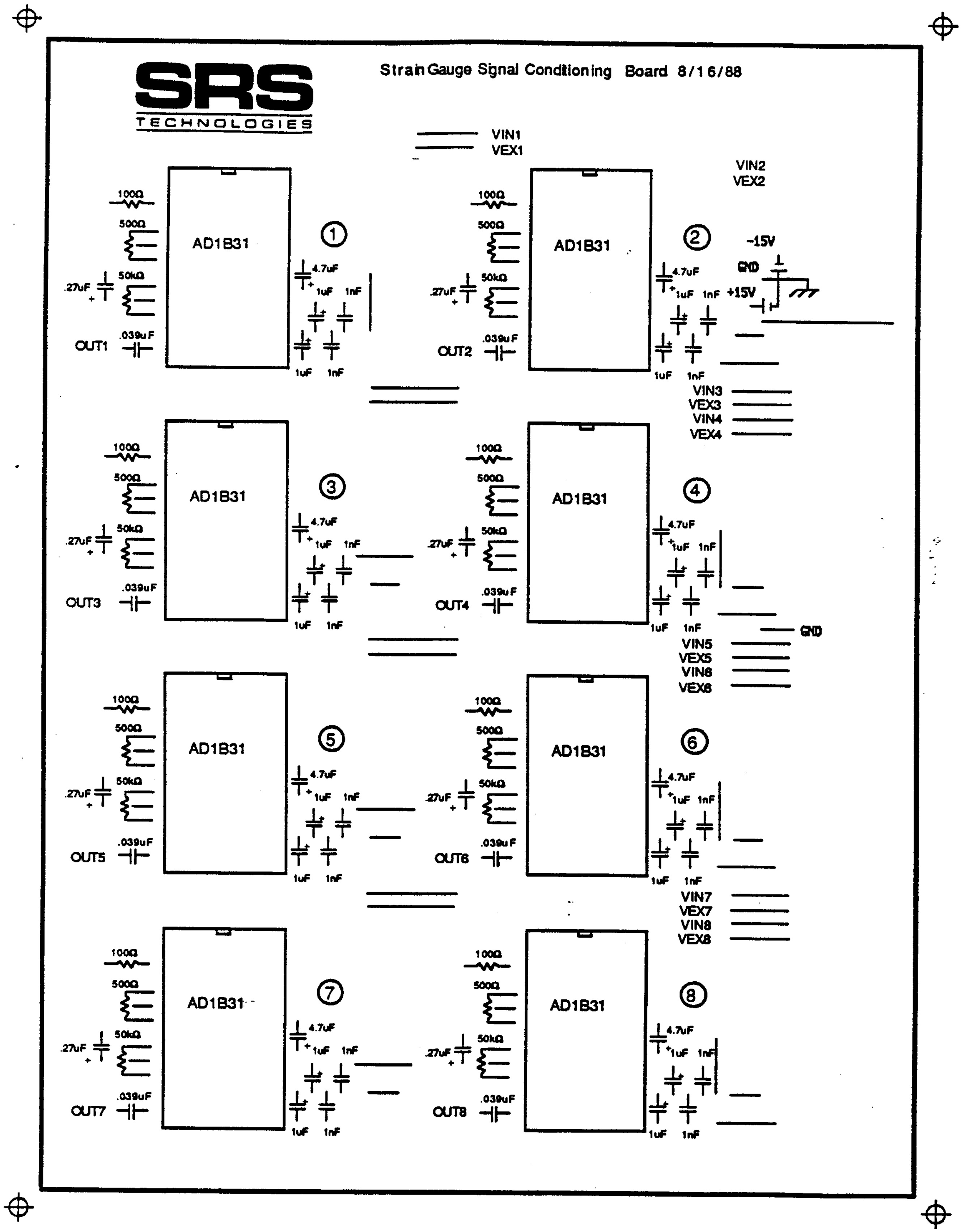


Figure 3.2.2-2. Strain Guage Signal Conditioning Board Silk Screen Layout

3.3 Three-Dimensional Target Tracking System

The resupply station is equipped with a three-dimensional target tracking system that allows the controller to know the precise coordinates of the PFMA end effector relative to the instrumented task board. This system is comprised of two Hamamatus (C2399-00) two-dimensional position sensor systems. The C2399-00 Position Sensor is an opto-electric position sensing unit designed to take advantage of the Position Sensitive Detector (PSD), and measures the two-dimensional position of a infrared target. The PSD is a light detecting element which makes use of a photo-diode. These functions enable the user to provide continuous position measuring and high-accuracy measuring for a moving infrared target at high speed because it is a non-discrete type, and able to obtain a quick response because it does not require scanning.

The C2399-00 lights the infrared target, corresponding to a pulse output from the control unit, and measures the position data by means of 312.5 Hz frequencies. An infrared filter and a built-in background-light eliminating circuit is provided in the sensor head. Therefore, no light intensity other than the infrared target can affect measuring. An accurate position measurement is performed optically with the target fitted on the object to be measured. This prevents position detection errors due to noise conduction from other objects, as may be encountered with ordinary vibrometers or accelerometers. Upon examination of the position sensor controller, it was noted that the manufacturer had modified their advertised position sensor system in order to eliminate cross talk between systems, when using the two systems together to obtain a three-dimensional location of an object. This modification was verified in SRS's laboratory through the testing of each position sensor system as a separate unit in a three-dimensional position detection system.

The position of the target, which is mounted on the PFMA's end effector tool, is recorded by the sensor head and the two-dimensional reference voltages transmitted as an analog input to the position controller. The sensor heads are mounted 78.375 inches along the X and Y axis from the center point of the resupply station's instrumentation board and 3 inches in the positive Z direction, as shown in Figure 3.3-1. By placing the sensor head 3 inches in the positive Z direction, a larger area of coverage in front of the instrumentation board is obtained. The area of coverage of the sensor heads is a 20° cone shape. This two-dimensional X-Y view of the area of coverage is shown in Figure 3.3-2. By placing the sensors heads 90° apart, the three-dimensional envelope of coverage resembles an odd shaped box. This arrangement will provide a three-dimensional location of the PFMA end effector tool in reference to the resupply station instrumentation board's center.

Each position sensor unit, or sensor head, sees a two-dimensional plane. The output of the position sensor control unit is in the range of ±5 volts, for each of the two-dimensions seen, corresponding to the location in which the light from the infrared target is projected onto the screen of the sensor head. Therefore, the output of the position sensor control unit describes a unique line in space, originating from the center of the position sensor head's lens, as shown in Figure 3.3-1

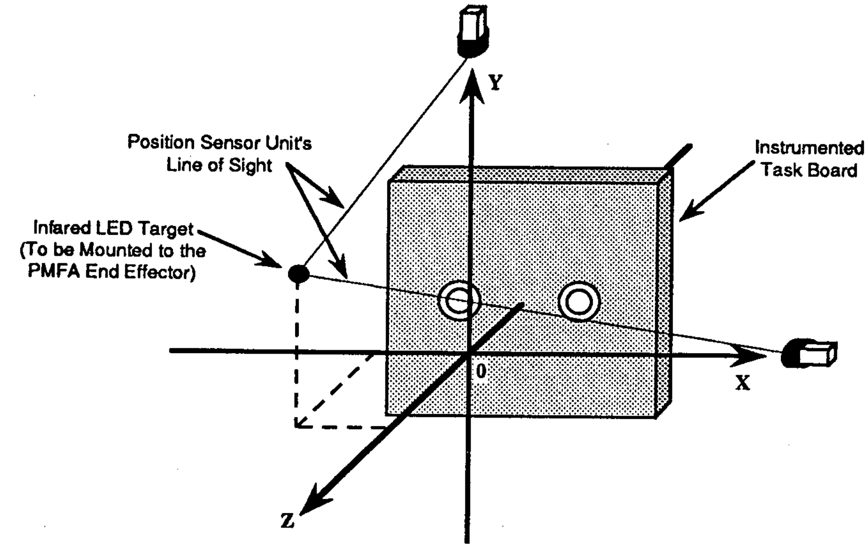


Figure 3.3-1 Target Tracking Systems Three-Dimensional Origin Location

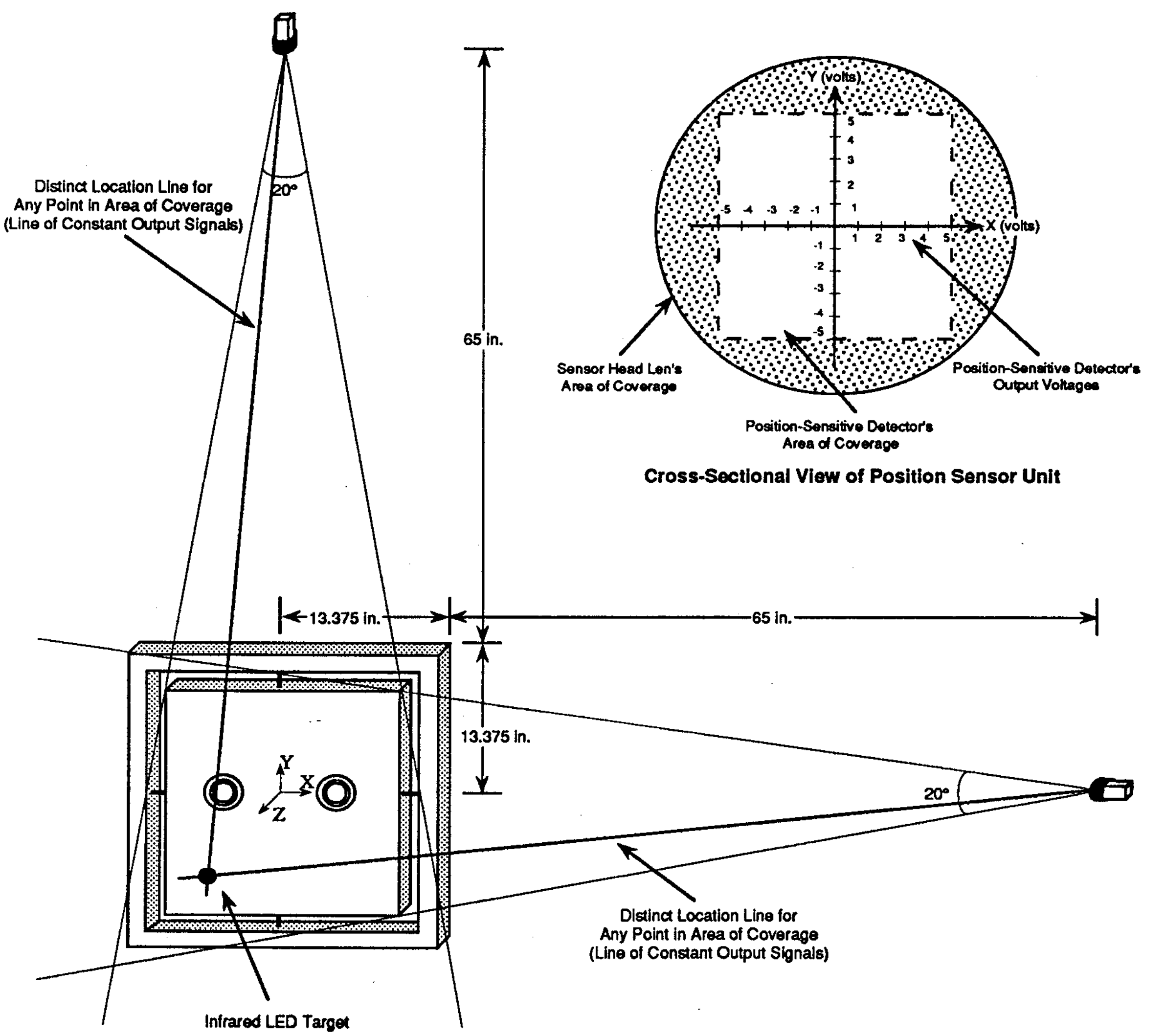


Figure 3.3-2 Configuration for the Target Tracking System, Showing the Area of Coverage

and Figure 3.3-2. The output of the position sensor head along each axis in a two-dimensional plane, as seen by a position sensor head, varies with the distance away from that plane due to the angular area of coverage.

In order to determine three-dimensional distance of the infrared LED target relative to the task board, equations describing distance along each axis relative to the position sensors output signals were developed by calibrating each position sensor unit at fixed location away from the chosen origin of the chosen three-dimensional coordinate system. From these calibration equations, the distance along any of the three-dimensional axes away from the origin is determined. Knowing the distance at which the line of sight of the position sensor unit, as shown in Figure 3.3-2, intersects each axis, the distance of the object from a fix origin can be calculated from the equations, shown below, defining the three-dimensional coordinates.

$$X = D_x - D_xD_y((X_o - D_x)/(X_oY_o - D_xD_y))$$
$$Y = D_y - D_xD_y((Y_o - D_y)/(X_oY_o - D_xD_y))$$
$$Z = Z_{01}Z_{02}D_y/(X_oZ_{01} - D_yZ_{02})$$

where:

- D_x The distance between the sensor placed on the X-axis and the origin.
- D_y The distance between the sensor placed on the Y-axis and the origin.
- X_o The distance along the X-axis at which the line of sight, from the sensor placed on the Y-axis, intersects it
- Y_o The distance along the Y-axis at which the line of sight, from the sensor placed on the X-axis, intersects it
- Z_{01} The distance along the Z-axis at which the line of sight, from the sensor placed on the X-axis, intersects it
- Z_{02} The distance along the Z-axis at which the line of sight, from the sensor placed on the Y-axis, intersects it

These three-dimensional position equations were integrated into LabVIEW and the data acquisition and control software, in order to calculate the location of the PFMA end effector relative to the center of the instrumented task panel. With this information, the PFMA operator can be evaluated on the basis of their ability to accurately control the PFMA.

3.4 Electronic Data Acquisition and Control System

The data acquisition and control system is used to monitor and record all the interaction of the PFMA operator with each instrumented task board, to control the fluid transfer operations, and to provide a optional compatibility of predetermining the reliability of the fluid transfer system's connectors. The data acquisition and control for the remotely operated fluid transfer demonstration system are achieved through the use of a Macintosh II, LabVIEW data acquisition/control software, Cricket Graph graphical data reduction software, and an analog-to-digital input/output PC board in series with an analog multiplexer board. This data acquisition and control system set up is shown in Figure 3.4-1.

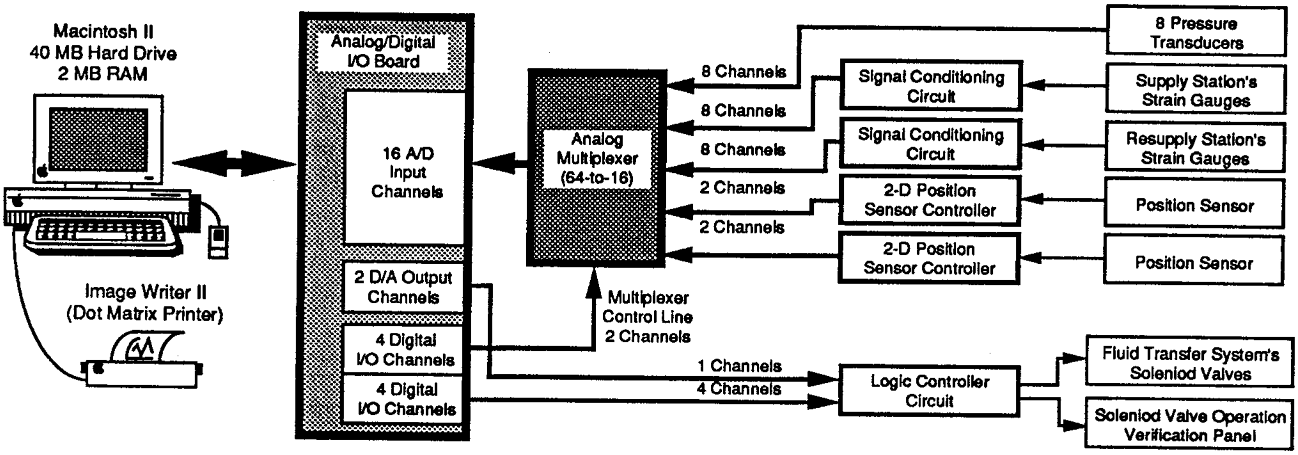


Figure 3.4-1 Electronic Data Acquisition and Control System

The Macintosh II consist of a 40 mega byte hard drive, 5 mega byte extended RAM, 4 bit video monitor card, color high-resolution monitor, and standard keyboard. The analog-to-digital input/output board (NB-MIO-16L-25) and the analog multiplexer (AMUX-64), developed by National Instruments, provides the computer with the ability to perform data acquisition on a maximum of 64 single ended channels, or 32 differential channels. The computer system is controlled with LabVIEW, a data acquisition and control graphical software developed by National Instruments. Graphical data reduction is accomplished with Cricket Graph software. Hard copies of the raw test data and graphs of the test performance can be obtained from the Image Writer II, a dot matrix printer. This computer system provides a user friendly environment along with efficiency.

3.4.1 System Automation Control Electronic Hardware

The operations of the solenoid valves used in the fluid resupply system are semi-automated in order to simplify the operations performed by the system operator. This was accomplished by utilizing the data acquisition system as a logic controller in which a sequence of solenoid valves are controlled, depending on the unique logic function. Through the use of a solenoid valve operation panel, the PFMA system operator is able to determine which valves are on or off and which valves are not operating properly. This option was added in order to reduce the time required to perform maintenance no the system, such as trouble shooting the electronics circuits and computer errors in the controlling of the solenoid valves.

In order to control the fluid resupply system's solenoid valves, a sequence of valve operations were determined and a unique logic function for each sequence was developed. Figures 4.2.2-1 and 4.2.2-2, in section 4.2.2, lists each system function, operation, valve sequence order, logic function code, and verification of the operation for liquid and gas transfer. A total of 39 solenoid valve sequences were defined in order for the system to be able to preform required operations. From this list, it was determined that a maximum of 26 logic functions (0-25) are needed to control the fluid resupply system, along with one noncontrol function (31). A chart showing the valve sequence order corresponding to the logic function code and solenoid valve openings is shown in Figure 3.4.1-1.

The solenoid valves are controlled by outputting a logic function code from the computer to a logic circuit that turns on a set of relays and activate the desired valves. LabVIEW is used to write a binary word to a four bit digital output port and one analog output ports of the A/D board. These outputs are connected to four 3 x 8 decoders, with three enable lines, which will provide the possibility of 32 logic operations. These outputs are connected to a series of logic gates which control each solenoid valve relay. The logic circuit is shown in Figure 3.4.1-2. A logic control circuit was designed to activate the relays controlling the solenoid valves. The logic circuit was constructed by using the wire wrapping method in order to accommodate any future change requirements and to reduce the circuit board size, as compared to the required printed circuit board size.

The solenoid valve sequences were semi-automated in order to activate each sequence separately. Initially, this was done in order to fine tune the system, determining the time required to verify the completion of each function. The fluid transfer system that was delivered could be further automated through LabVIEW software. Related chronological operations can be controlled by selecting a single switch located on the LabVIEW panel on the computer screen.

In order to verify that each relay is activating the appropriate solenoid valve when required, a valve operation verification panel was designed. The system's operator is able to determine which valves are not operating properly, through the use of the fluid transfer solenoid valve operation verification panel. A neon light was connected in parallel with each solenoid valve, at the corresponding relay that activates that solenoid valve, to verify whether the solenoid is receiving current. The panel, which is placed near the system operator, consists of a simplified version of the fluid transfer system's hardware schematic, with each solenoid valve's representative neon light illuminated when activated. The panels simplified schematic is shown in Figure 3.4.1-3.

During the demonstration, the output of the 9 pressure transducers are displayed on the computer screen as digital readouts. Four of these pressure transducers along with some additional software can be utilized in order to determine the helium leakage rate of the system prior to the

	SEQUENCE ORDER	FUNCTION CODE	SV1	SV2	SV3	SV4	SV5	SV6	SV7	SV8	SV9	SV10	SV11	SV12	SV13	HVV1	HVV2	HVV3	HVV4	HSV1	HSV2	HSV3	HSV4	ISV1	ISV2	ISV3	ISV4
LIQUID TRANSFER OPERATIONS	1	0						●	●																		
	2	1				●						●		●	●												
	3	2						●																			
	4	3					●			●																	
	5	4														●				●				●			
	6	5																		●				●			
	7	6																						●			
	8	7																●				●				●	
	9	8																				●				●	
	10	9																								●	
	11	10																●									
	12	11																●		●				●			
	13	5																		●				●			
	14	6																						●			
	15	10																●									
	16	12	●	●		●							●														
	17	31	NONCONTROL CODE																								
	18	13																		●						●	
	19	9																								●	
	20	14																●								●	
	21	31	NONCONTROL CODE																								
	22	15											●														
	23	31	NONCONTROL CODE																								
GAS TRANSFER OPERATIONS	24	2						●																			
	25	16															●				●				●		
	26	17																			●				●		
	27	18																							●		
	28	19																	●				●				●
	29	20																					●				●
	30	21																									●
	31	22																	●								
	32	23																	●		●				●		
	33	17																			●				●		
	34	18																							●		
	35	22																	●								
	36	24			●						●																
	37	31	NONCONTROL CODE																								
	38	25			●						●								●								
	39	31	NONCONTROL CODE																								

Figure 3.4.1-1. Logic Solenoid Sequence Chart

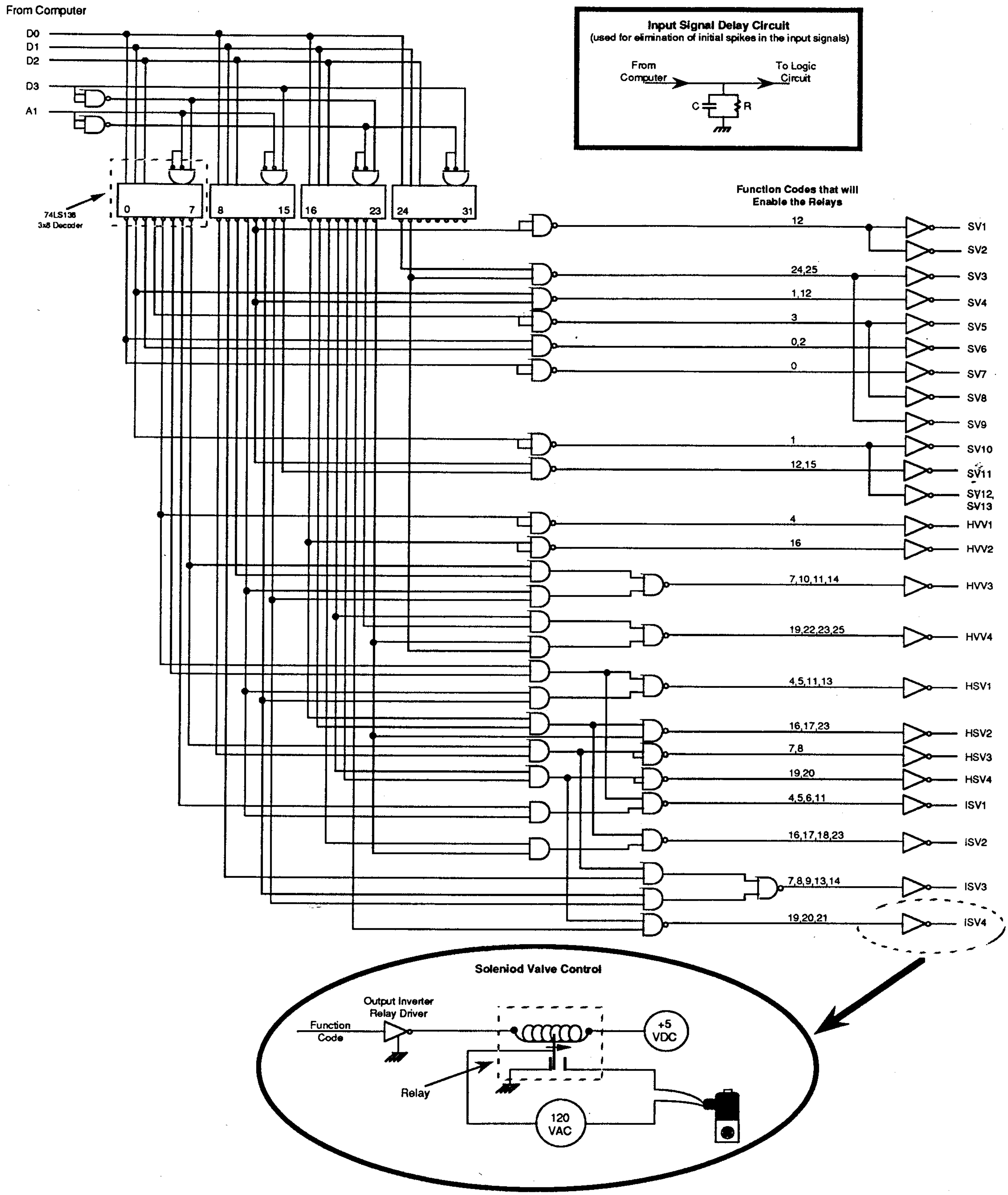


Figure 3.4.1-2. Logic Network for Solenoid Valves Sequence control

transfer of fluid. The data from the four pressure transducers are recorded in a file on the hard disk that can be used to calculate the helium leakage rate. This leakage rate can then be used to determine a relationship between the helium leakage rate and a water, or air, leakage rate for a given section of the fluid transfer system's pumping circuit. If the system is reliable, a pop-up screen should tell the operator to "Proceed with the Operation", or if the system is not reliable a pop-up screen should tell the operator to "Discontinue the Operation, the System is Unreliable".

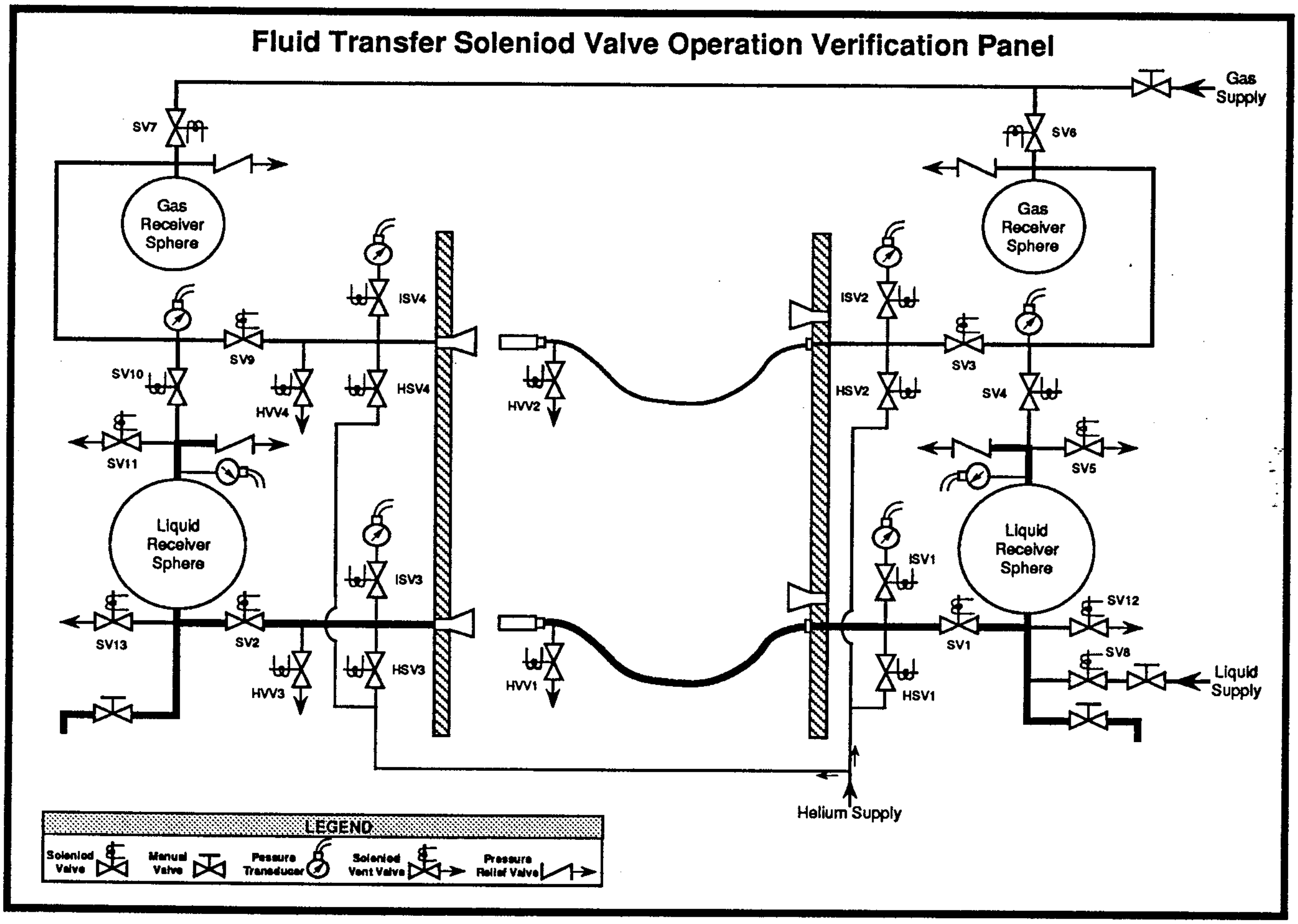


Figure 3.4.1-3. Simplified Schematic for Fluid Resupply System Panel

3.4.2 Data Acquisition and Control Software

LabVIEW serves as a software driver and controller for the NB-MBIO-16 (analog-to-digital board) and AMUX-64 (8-to-64 analog multiplexer) hardware data acquisition boards installed in the Macintosh II. LabVIEW is a complete programming environment which allows the user to construct virtual instruments (VI's) that control and record operations that are required. The requirements for the fluid transfer demonstrations were addressed and evaluated. LabVIEW sub-VI's were constructed to perform the requirements of the demonstrations. The final instrument design includes integration of the sub-virtual instruments into a single virtual instrument for simultaneous data acquisition and control.

The building block of LabVIEW is the Virtual Instrument (VI). The VI's in LabVIEW are the software components of the complete data acquisition and control system installed in the Macintosh II. Each VI has a front panel which specifies the inputs and outputs of the program. Figure 3.4.2-1 represents the controls and indicators which can be used in a front panel. Behind the front panel in LabVIEW is a block diagram which represents the actual executable program. The diagram represents graphical programming functions that are standard in any programming environment. Any VI that is designed can be represented as an icon that can be included in other VI's. The hierarchical structure of LabVIEW enables the user to construct complicated control and acquisition systems from combining the VI into one complete VI.

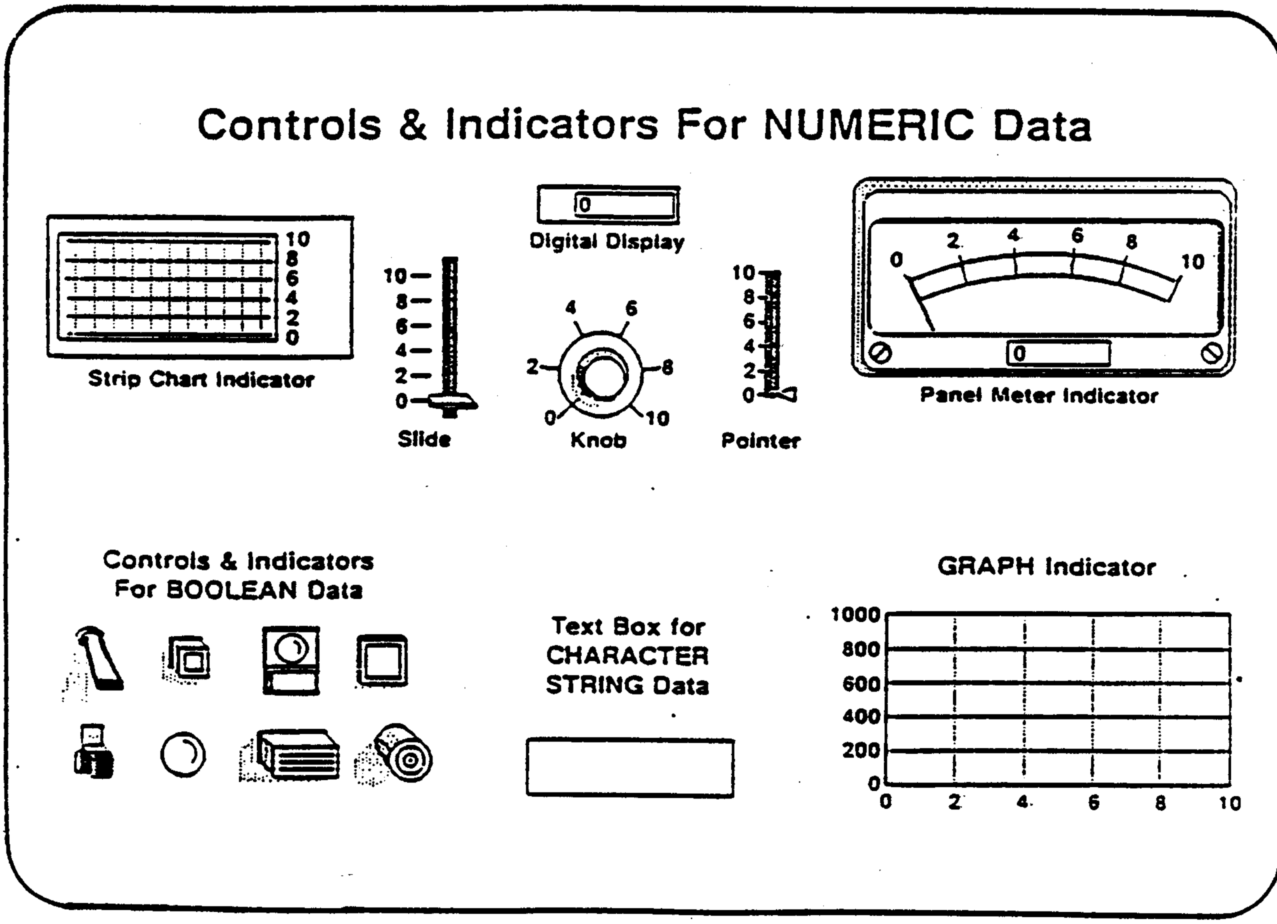


Figure 3.4.2-1. LabVIEW's Front Panel Controls and Indicators

Several operations will be performed during the gas and fluid resupply demonstrations. Each operation requires some type of system control or data acquisition from the Macintosh II/LabVIEW system. The requirements that were addressed are described in Figure 3.4.2-2.

REQUIREMENTS	PURPOSE
Valve Sequence	Digitally Control Output Ports to Change Solenoid Valve Positions
Load Measurements	Measure and Store Analog Signals from Strain Gauge Conditioning Circuits to Determine Loads on Task Boards During Mating/Demating of Connectors
Pressure Measurements	Measure and Store Analog Signals from Pressure Transducers During Fluid Transfer Operations
Helium Leak Test	Provide the Capability to Calculate Helium Leakage Rate Through Connectors from Pressure Transducers Signals
Position Measurements	Measure and Store Analog Signals from Position Sensors During Operation of PFMA

Figure 3.4.2-2. LabVIEW Requirements for the Fluid Transfer System

A sequence valve VI was constructed using LabVIEW. The VI enables the user to control the solenoid valves by selecting the proper sequence in the front panel. The automated sequence valve instrument allows the user to specify the time duration between each sequence. The instrument is used for complete automated control of the solenoid sequences used in the PFMA demonstration. Execution of the instrument sends the proper digital output port commands to the digital I/O ports on the NB-MIO-16 board. Arrays and indexes in the LabVIEW block diagram were used in order to correspond the sequence number selected to the proper digital output configuration. Several sub-VI's were used in the program to initialize the digital output ports and write the binary data to the board. These instruments are transparent to the operator of the system and only the sequence valves' VI is executed.

The load measurement VI consists of data acquisition, storage and real-time graphics of the analog channels for measurement of the loads on the supply and resupply panels. A double buffer acquisition system is used in LabVIEW. The system allows the programmer to store information in a buffer while scanning the channels of interest on the A/D board. The buffer is then periodically read and stored in the desired file on the computer. The data is plotted on the screen while simultaneous data acquisitions are occurring. An external gate is also used for triggering data acquisitions. The external gate enables data acquisitions while the gate is held in a high status. The external gate enables the board to perform a scan of the channels at a high rate, but allow for a time delay between each scan. The time delay is determined by the desired acquisition rate. The displacement measurement VI records and plots four analog signals from the position sensors. This VI is incorporated into the load measurement VI for simultaneous operations.

The pressure measurement VI is constructed similar to the load measurement VI but is a stand alone instrument. This VI scans the channels selected and stores the information on disk for post processing and in memory for real time display of the pressure transducers of interest. The leak rate VI will calculate the helium leak rate of the pressure transducer selected on the front panel of the Fluid Transfer Instrument.

The main Fluid Transfer VI consists of a combination of all the virtual instruments described previously. The front panel design of the main VI is shown in Figure 3.4.2-3. The panel allows the user of the system to perform all task requirements of the fluid transfer demonstration. The front panel consists of binary switches, numeric input controls and numeric output controls. The numeric input controls enable the user of the system to change the sequence of the solenoid valves and select the proper pressure transducers for leak checks. A binary slide switch is used in the front panel to select the task to be performed. Once the task is completed, the user can continue with another task selection. Numeric output controls consist of the supply/resupply panel forces, pressure transducer indicators and position sensor indicators. The binary switches on the front panel are used to initiate and suspend task operations during the fluid transfer demonstration.

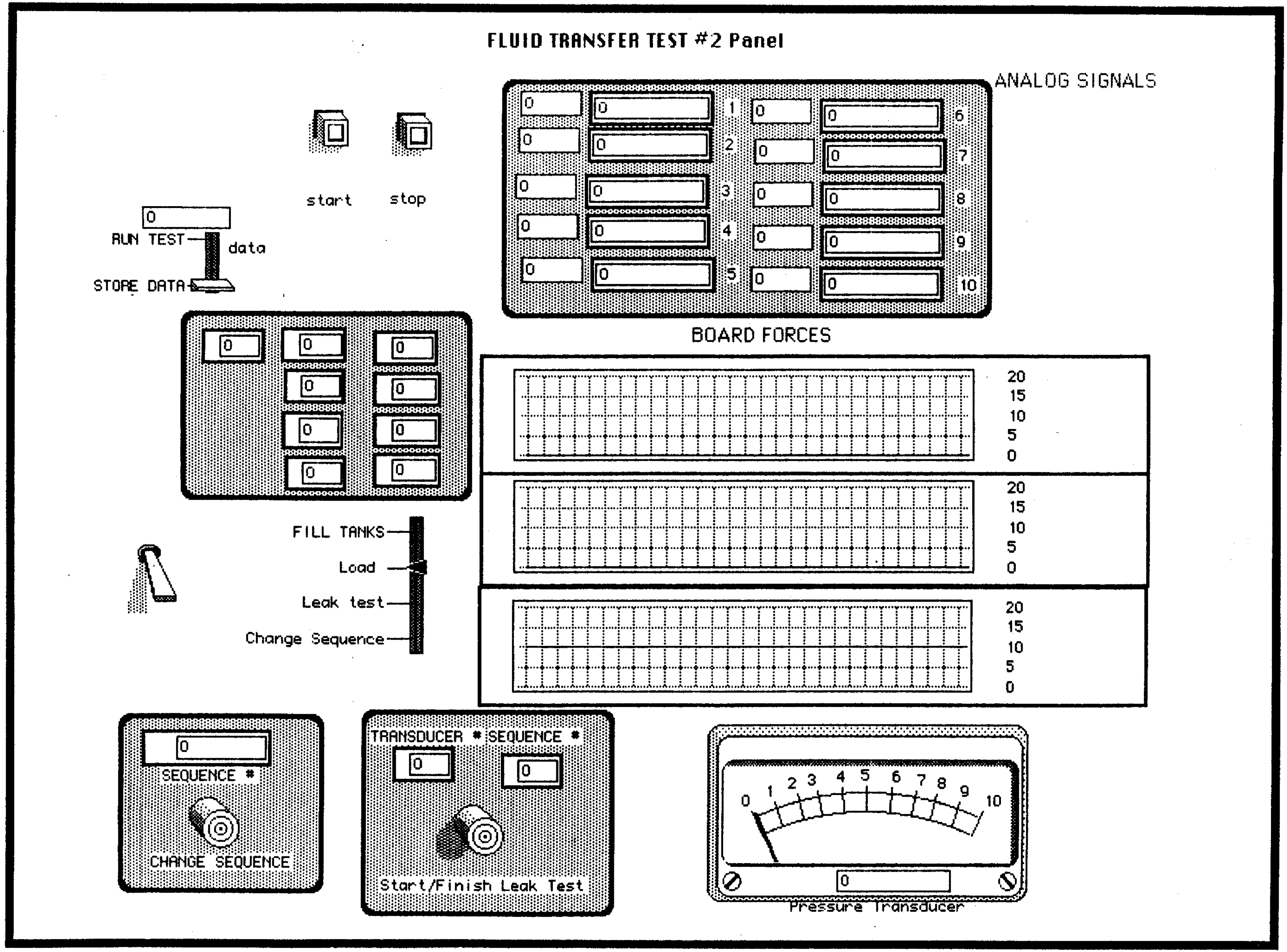


Figure 3.4.2-4. Design of LABVIEW Front Panel for Fluid Transfer Demonstration System

4.0 SYSTEM EVALUATION AND TESTING

The objective of the demonstration tests are to demonstrate and evaluate the operations involved in an on-orbit fluid transfer and that they can be accomplished by a remotely controlled robotic arm with appropriate end effectors. Specific objectives are as follows:

- Demonstrate the capability of the fluid transfer demonstrator to satisfactorily simulate the major operations involved in a remotely operated on-orbit fluid transfer.
- Develop data, experience and methodology for evaluating operator skills for conducting the fluid transfer operations.
- Demonstrate a concept for remote leak detection and minimizing the potential for spills of toxic fluids.
- Provide experience and design information for improving teleoperator capability, and on-orbit fluid transfer system designs and operations.

4.1 Test Requirements

All tests were conducted using ambient temperature air to represent the pressurant and water to represent the liquid propellant. The fluid transfer system simulates the transfer of pressurant gas or liquid propellant. The type of fluid to be transferred will establish the specific operations and sequences. Prior to each demonstration, the fluid transfer demonstrator will be filled with the appropriate fluids. The water tank need not be filled if only pressurant transfer is to be demonstrated. The demonstration of liquid transfer requires the following operations:

- Fill pressurant tanks with air from a facility source
- Fill water tanks from the facility source
- Conduct remote leak checks of liquid connectors prior to committing to liquid transfer
- Conduct transfer operations
- Purge connector circuits prior to disconnect
- Disconnect and stow liquid connector.

The demonstration of gas transfer requires the following operations:

- Fill pressurant tanks with air from a facility source
- Conduct remote leak checks of gas connector circuits
- Conduct transfer operations
- Disconnect and stow gas connectors.

 A.

4.2 Test Procedures

The fluid transfer demonstrator is designed to simulate the remote transfer of both liquid and gas. The following sections describe the procedures for demonstrating liquid and gas transfer operations.

4.2.1 Fluid Connectors Leakage Detection

Prior to committing to the transfer of liquid, the servicing and receiving connectors will be leak checked in the disconnected and connected configurations. In the disconnected configuration, helium will be supplied to the connectors and the leakage determined by the loss of pressure in the pressurized volume. After these checks are performed, the connectors will be remotely mated with the PFMA. During these operations, the forces and moments generated during the mating and demating operations will be measured and recorded. The position history generated during these operations by the PFMA will be recorded. Major operations will be timed and this data will be used for evaluation of the PFMA and operator capability. After successful mating of the fluid connectors, the connector interface will be leak checked by helium pressure and monitoring the pressure decay rate.

4.2.2 Demonstration of Liquid Transfer

The air and water tanks must be filled from facility sources before proceeding with the transfer demonstration. All valves isolating the air tank must be closed and the valve allowing facility air to flow into the tank must be opened. The pressure to the air tank should be regulated to 90 psig. The facility valve will be closed when the air tank pressure reaches 90 psig. The water tank will be filled from the facility water source. Prior to filling the water tank, the air on the water side of the bladder must be expelled (see Figure 3.1-1). Vent valve SV12, as shown in Figure 3.1-1, must be opened and the water tank pressurized by opening SV4. When the water tank pressure reads 10 psig, SV4 and SV12 should be closed. This positions the bladder to the lower half of the water tank. All valves isolating the water tank, with the exception of the vent valves, will be closed. The vent valves, SV5, will be opened to allow air behind the bladder to escape as the water tank is filled. The facility water valve will be opened to allow water to fill the water tank. After filling is complete, the facility water valve and the water tank vent valve will be closed.

Liquid will be transferred from the servicer water tank to the receiver water tank. During this operation, pressures in the servicer pressurant and water tanks and in the receiver water tank will be measured and recorded. Transfer completion can be verified by visual observation, and by tank pressure.

After completion of the liquid transfer, the connector liquid lines should be purged prior to disconnect and storage. The liquid circuit will be isolated from the water tanks and helium supplied to the circuit to purge residual water in the lines. After this operation, the lines will be disconnected and stowed with the PFMA. Following all tests the water tanks will be drained. Forces and moments generated during this operation will be measured and recorded. The operation envelope history of the PFMA will be recorded. Each operation will be timed and this data will be used to evaluate the PFMA and operator capability.

The procedures required to operate the remote fluid transfer demonstrator have been synthesized into functions, operations and verification that the operation was successfully completed. Shown in Figure 4.2.2-1 are the functions, operations, and verifications that are involved in preparing the system for liquid transfer, conducting the leak checks, and conducting the transfer operations including passivating the system after completion of the demonstration.

4.2.3 Demonstration of Gas Transfer

The air tank is to be filled from a facility source before proceeding with the pressurant transfer demonstration. All valves isolating the service air tank will be closed except the facility air valve which will be opened to pressurize the air tank to 90 psig. Prior to committing to transfer of pressurant, the servicing and receiving connectors will be leak checked in the disconnected and connected configuration. In the disconnected configuration, helium should be supplied to the connectors and the leakage determined by the pressure decay rate of the pressurized volume. After these checks are performed, the connectors will be mated using the PFMA. During this operation, the forces and moments generated will be measured and recorded. The position history generated by the PFMA during these operations will be recorded. Major operations will be timed and these data will be used for evaluation of the PFMA and operator capability. After successful mating, the connector interfaces will be leak checked by applying helium pressure and monitoring the pressure decay rate.

Gas will be transferred from the servicer to the receiver tank. Pressures in the servicer and receiver tanks will be measured and recorded. The transfer will be complete when the pressures in each tank are essentially equal. After transfer is complete the PFMA will be used to disconnect and stow the servicing connector. Forces, moments, and times for each operation will be recorded. Following all tests, the air tanks will be vented to ambient pressure. Shown in Figure 4.2.2-2 are the functions, operations, and verifications that are required in preparing the system and conducting pressurant gas transfer including stowing the connectors and depressurizing the gas bottles.

4.3 Evaluation Criteria

Data required from the Remote Fluid Transfer System are pressures, pressure histories, and average flow rates. The average flow is determined by the volume of fluid transferred and the transfer time. The data required for evaluation of operator performance includes the time for each operation required by the PFMA, the forces and moments imparted to the task boards, and the

FUNCTION	OPERATION	Sequence Order	Function Code	VERIFICATION
SYSTEMS READINESS CHECK	Close HV3, HV4 / Open HV1, HV2 — Manual Operation Set Helium Tank Low Pressure Regulator Open Helium Tank Low Pressure Hand Valve			Low Pressure Gage Reading = 15 PSIG Observe Helium Tank Low Pressure (Output) Gage = 15 PSIG
FILL SERVICER AND RECEIVER GAS TANKS (AIR)	Open SV6, SV7 Close SV6, SV7	1	0	Observe Gas Tank Press PT1 and PT2 = 90 PSIG
EXPELL AIR FROM 2 FLUID TANKS	Open SV4, SV12, SV10, SV13 Close SV4, SV12, SV10, SV13	2	1	Observe Bladders of Both Servicer and Receiver Fluid Tanks Move to Negative Position Observe PT7 and PT8 Pressure Decay from 50 PSIG Toward Zero.
REFILL SERVICER GAS TANK	Open SV6 Close SV6	3	2	Observe Pressure PT1 = 90 PSIG
FILL SERVICER FLUID TANK (WATER)	Open SV8, SV5 Close SV8, SV5	4	3	Visual Observation of Filling Operation Bladder in Servicer Fluid Tank Goes Positive PT7 Pressure Decays to Zero

* All Soleniod Valves in the Rest Position
(Normally Closed When Deenergized Electrically)

880801GC1115

Figure 4.2.2-1. Liquid Transfer Demonstration Systems Operation

FUNCTION	OPERATION	Sequence Order	Function Code	VERIFICATION
FLUID TRANSFER DEMONSTRATION:				
LEAK CHECK SERVICER CONNECTOR (PUROLATOR SOCKET)				
• Purge Servicer Fluid Line	Open ISV1, HSV1, HVV1	5	4	PT4 Indicates Positive Pressure in the Range 0-15 psig
• Leak Check	Close HVV1	6	5	PT4 Indicates 15 psig
	Close HSV1	7	6	Observe Pressure Decay, PT4 PT4 < TBD Acceptable PT4 > TBD Unacceptable
• Upon Completion of Leak Check	Close ISV1			
LEAK CHECK RECEIVER CONNECTOR (PUROLATOR RECEPTACLE)				
• Purge Receiver Fluid Line	Open ISV3, HSV3, HVV3	8	7	PT5 Indicates Positive Pressure in the Range 0-15 psig
• Leak Check	Close HVV3	9	8	PT5 Indicates 15 psig
	Close HSV3	10	9	Observe Pressure Decay, PT5 PT5 < TBD Acceptable PT5 > TBD Unacceptable
• Upon Completion of Leak Check	Close ISV3			
	Open HVV3	11	10	
MATE TWO HALVES OF PUROLATOR FLUID CONNECTOR	Grasp Servicer Half of Connector With PFMA and Connect to Receiver Half			Visual (Red Light Appears When Mated)

880801GC1130

Figure 4.2.2-1. Liquid Transfer Demonstration Systems Operation (Continued)

FUNCTION	OPERATION	Sequence Order	Function Code	VERIFICATION
LEAK CHECK FLUID CONNECTOR IN THE MATED CONFIGURATION				
• Purge Fluid Line	Open ISV1, HSV1, HVV3	12	11	PT4 Indicates Positive Pressure in the Range of 0-15 psig
	Close HVV3	13	5	Pressure PT4 = 15 psig
• Leak Check	Close HSV1	14	6	Observe PT4 Pressure Decay PT4 < TBD Acceptable PT4 > TBD Unacceptable
• Upon Completion of Leak Check	Close ISV1 Open HVV3	15	10	
TRANSFER FLUID FROM SERVICER TO RECEIVER TANK	Open SV4, SV1, SV2, SV11	16	12	Observe PT7 Pressure Decay From 50 psig Toward Zero Observe Bladder Position in Fluid Servicer Tank Going Negative Observe Bladder Position in Fluid Receiver Tank Going Positive
Upon Completion of Transfer	Close SV4, SV1, SV2, SV11	17	31	Transfer Complete, Observe Receiver Tank Full
PURGE TRANSFER FLUID LINE PRIOR TO DISCONNECTING FROM THE RECEIVER TANK	Open HSV1, ISV3	18	13	PT5 Indicates 15 psig
	Close HSV1 (Helium Supply)	19	9	
	Open HVV3	20	14	PT5 Pressure Decay to Zero
	Close ISV3, HVV3	21	31	
STOW CONNECTOR IN SERVICER STOWAGE RECEPTACLE	PFMA Disconnects Purolator Connector and Stows in Servicer Panel			Visual
NOTE: IF NECESSARY TO DRAIN THE RECEIVER FLUID TANK	Open HV4, SV11	22	15	Visual
Upon Completion of Drain	Close HV4, SV11	23	31	

880801GC1230

Figure 4.2.2-1. Liquid Transfer Demonstration Systems Operation (Continued)

FUNCTION	OPERATION	Sequence Order	Function Code	VERIFICATION
SYSTEMS READINESS CHECK	Close HV3, HV4, HV1 (Fluid Valve) Open HV2 Open Helium Supply Low Press Hand Valve			Observe Helium Pressure = 15 psig (Low Pressure (PR) Previously Set To 15 psig)
FILL SERVICER GAS TANK	Open SV6	24	2	Observe PT1 = 90 psig
	Close SV6			
LEAK CHECK SERVICER CONNECTOR (FAIRCHILD SOCKET HALF)				
• Purge Servicer Gas Line	Open HSV2, ISV2, HVV2	25	16	PT3 Indicates Positive Pressure (0-15 psig)
• Leak Check	Close HVV2	26	17	PT3 Indicates 15 psig
	Close HSV2	27	18	Observe Pressure Decay of PT3 PT3 > TBD Unacceptable PT3 < TBD Acceptable
• Upon Conpletion of Leak Check	CLOSE ISV2			PT3 Reads Zero
LEAK CHECK RECEIVER CONNECTOR (FAIRCHILD RECEPTACLE HALF)				
• Purge Receiver Gas Line	Open HSV4, ISV4, HVV4	28	19	PT6 Indicates Positive Pressure (0-15 psig)
• Leak Check	Close HVV4	29	20	PT6 Indicates 15 psig
	Close HSV4	30	21	Observe Pressure Decay of PT4 PT6 > TBD Unacceptable PT6 < TBD Acceptable
• Upon Completion of Leak Check	Close ISV4 Open HVV4	31	22	PT6 Reads Zero

* All Soleniod Valves in the Rest Position (Normally Closed When Deenergized Electrically)

880801GC1315

Figure 4.2.2-2. Gas Transfer Demonstration System Operation

FUNCTION	OPERATION	Sequence Order	Function Code	VERIFICATION
MATE TWO HALVES OF FAIRCHILD CONNECTOR	Grasp Servicer Half of Connector With PFMA and Connect to Receiver Half			Visual (Red Light Indicates Mated)
LEAK CHECK GAS CONNECTION WITH TWO HALVES MATED:				
• PURGE GAS LINE	Open ISV2, HSV2, HVV4	32	23	PT3 Indicates Positive Pressure (0-15 psig)
• LEAK CHECK	Close HVV4	33	17	PT3 Indicates 15 psig
	Close HSV2	34	18	Observe Pressure Decay of PT3: PT3 > TBD Unacceptable PT3 < TBD Acceptable
• Upon Completion of Leak Check	Close ISV2	35	22	PT3 Reads Zero
TRANSFER GAS	Open SV3, SV9	36	24	Observe PT1 Drops to 45 psig Observe PT2 Increases to 45 psig Gas Transfer Completed
	Close SV3, SV9	37	31	
DEPRESSURIZE GAS SYSTEM LINES	Open HVV4	38	25	PT1 and PT2 Drop to Zero
	Close HVV4, SV3, SV9	39	31	
STOW SERVICER HALF OF GAS CONNECTOR IN STOWAGE RECEP-TACLE	Grasp Servicer Half of Gas Con-nector With PFMA, Demate and Return to Servicer Receptacle			Visual

880801GC1340

Figure 4.2.2-2. Gas Transfer Demonstration System Operation (Continued) position coordinates of the PFMA's end effort relative to the receiving connectors. Figure 4.3-1 shows the format for providing operator skill evaluation data related to performing tasks, with the PFMA, which are required to conduct a fluid transfer operation with the remote fluid transfer demonstrator. Operator tasks not requiring the PFMA such as loading the fluid transfer tanks, initial leak checks etc., are not included in the task evaluations because they do not require skill in operating the PFMA.

Following each test series, the data will be reduced to allow completing the skill evaluation forms, as shown in Figure 4.3-1. Additional tabular or graphical data that is needed to identify anomalies and/or problems that may influence subsequent runs can be provided. A test report can be prepared at the completion of the test program to document the significant overall results and conclusions.

OPERATOR NAME ____________________

DATE OF TEST ____________________

OPERATIONS	DESCRIPTION	EVENT TIME	RECEIVER FORCES/TORQUES							RESUPPLY FORCES/TORQUES							END EFFECTOR DISPLACEMENT		
			MAX FORCE				MAX TORQUE			MAX FORCE				MAX TORQUE					
			Fx	Fy	Fz	Fr	Tx	Ty	Tz	Fx	Fy	Fz	Fr	Tx	Ty	Tz	X	Y	Z
PREPOSITION ARM	ARM & JAWS ARE ALLIGNED FOR GRASPING TOOL HANDLE																		
MOVE ARM	ARM IS MOVED TO POSITION JAWS AROUND TOOL HANDLE																		
TURN	ROTATE WRIST TO DISENGAGE TOOL																		
MOVE ARM	ARM TRANSPORTS TOOL TO FLUID CONNECTOR																		
PREPOSITION ARM	ARM AND END EFFECTOR TOOL ARE ALIGNED FOR MATING OF FLUID CONNECTOR																		
INSERT	ARM IS MOVED TO POSITION TOOL ROLLERS INTO MATING SLOT																		
TURN	ROTATE WRIST TO ENGAGE CONNECTOR HALVES																		
PAUSE	CONDUCT LEAK CHECK IN MATED CONFIGURATION																		
TRANSFER FLUID	OPEN VALVES TO TRANSFER FLUID-OBSERVE TANK PRESSURES TO CONFIRM TRANSFER																		
RELEASE	OPEN JAWS & MOVE ARM																		

Figure 4.3-1. Operator Skill Evaluation Form for Remote Fluid Transfer Demonstration

OPERATOR NAME ____________________

DATE OF TEST ____________________

OPERATIONS	DESCRIPTION	EVENT TIME	RECEIVER FORCES/TORQUES							RESUPPLY FORCES/TORQUES							END EFFECTOR DISPLACEMENT		
			MAX FORCE				MAX TORQUE			MAX FORCE				MAX TORQUE					
			Fx	Fy	Fz	Fr	Tx	Ty	Tz	Fx	Fy	Fz	Fr	Tx	Ty	Tz	X	Y	Z
PREPOSITION ARM	ARM & JAWS ARE ALLIGNED FOR GRASPING TOOL HANDLE																		
MOVE ARM	ARM IS MOVED TO POSITION JAWS AROUND TOOL HANDLE																		
GRASP	CLOSE JAWS AROUND TOOL HANDLE																		
PAUSE *	PURGE LIQUID LINES WITH HELIUM TO REMOVE RESIDUALS- CLOSE VENT & HELIUM VALVES																		
TURN	ROTATE WRIST TO DISENGAGE TOOL																		
MOVE ARM	ARM TRANSPORTS TOOL TO STOWAGE																		
PREPOSITION ARM	ARM AND END EFFECTOR TOOL ARE ALLIGNED FOR MATING WITH STOWAGE CONNECTOR																		
INSERT	ARM IS MOVED TO POSITION ROLLERS INTO MATING SLOT																		
TURN	ROTATE WRIST TO ENGAGE CONNECTORS																		
RELEASE	OPEN JAWS & STOW ARM																		

* THIS OPERATION MAY NOT BE REQUIRED FOR GAS TRANSFER

Figure 4.3-1. Operator Skill Evaluation Form for Remote Fluid Transfer Demonstratrion (Continued)

5.0 CONCEPT DEFINITION OF IN-VACUUM TEST BED

The following sections provide the conceptual design and integration for a fluid transfer concept to demonstrate the transfer of fluids in a vacuum environment. In addition to demonstrating the fluid transfer operations, methods for evaluating fluid leakage in vacuum are identified.

The limitations of the vacuum testing chamber and the PFMA dictate the restrictions placed on the in-vacuum test bed set up. The vacuum facility selected by MSFC is the Sunspot Thermal-Vacuum Facility located in building 4619. This chamber has a 10.5 foot diameter by 12 foot high test volume which is too small to accommodate the protoflight manipulator arm (PFMA). The characteristics of the PFMA including arm dimensions are shown in Figure 1.1.2-1, located in section 1.1.2. Due to these restrictions, the in-vacuum transfer demonstration is limited to manually connecting the fluid connectors, and investigating the leakage characteristics of the connectors. The fluid transfer system concept is essentially the same as designed for the ambient fluid transfer demonstrations with the exception of providing vacuum compatible fluid hoses and solenoid values for isolating the connectors for remote leak checks.

5.1 Facility Interfaces

The Sunspot chamber has "feed thrus" for providing fluid and electrical connections from outside the chamber to test articles in the chamber. There are also viewing ports for observing test specimens. Residual gas analyzers are also available for gas analysis, and a centralized data acquisition system is available for data collection and processing. As previously stated, the chamber has a 10.5 foot diameter by 12 foot high test section which can be evacuated to 5×10^{-9} torr. The design concept for the in-vacuum fluid transfer demonstration provides a test panel containing the receiver side fluid connectors, and a storage rack for the supply side fluid connectors to be placed in the vacuum enclosure. The fluid connections should be made manually and the chamber evacuated prior to the fluid transfer operation. The fluid lines are routed through the vacuum chamber feed thrus to their respective fluid tanks which are located outside the chamber. The design of these tanks, supporting structures, and controls are the same as for the one atmosphere system.

5.2 In-Vacuum Demonstration System Concept Definition

The component design and system operation is the same for the one atmosphere and in-vacuum demonstrator with the exception of the connector mounting hardware that should be placed in the vacuum chamber. This hardware is relatively simple consisting of a 20 inch square .125 inch thick aluminum panel fastened to an aluminum frame mounted on a four foot tall stand. The panel can accommodate both the male and female connectors as shown in Figure 5.2-1. The mate/demate of the connectors will be performed manually at ambient pressure. The arrangement of the isolation valves for remote leak checking is the same as for the one atmosphere design.

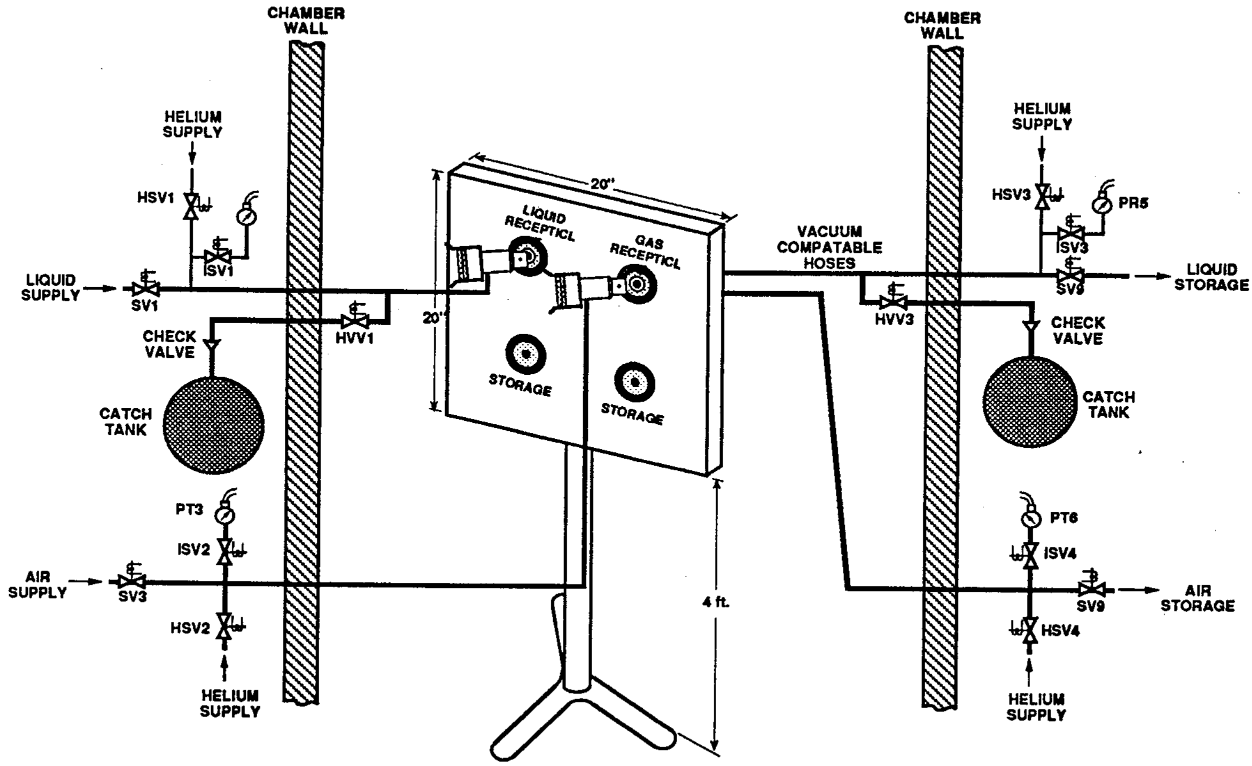


Figure 5.2-1. Concept for Mounting Fluid Connectors in Vacuum Chamber

The overall system concept is shown in Figure 5.2-2. The one atmosphere design is integrated with the vacuum chamber and the support stand as shown. Once the connectors have been leak checked and mated manually the chamber can be evacuated and the fluid transfer operations implemented. The procedures and sequences for the transfer operations are the same as described for the one atmosphere system.

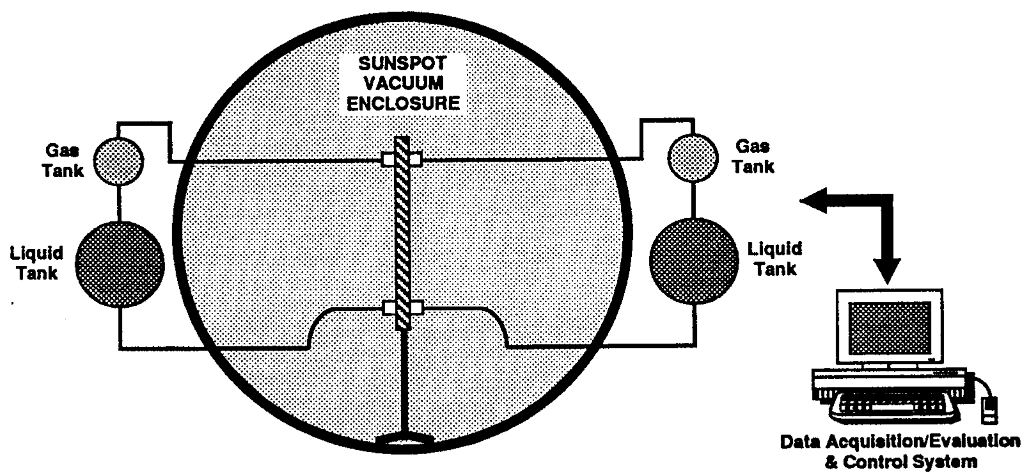


Figure 5.2-2. One Atmosphere Fluid Transfer Demonstrator Integrated with Vacuum Chamber

5.3 In-Vacuum Fluid Connectors Leak Check

The minimization of leaks or spills is accomplished by leak checks of both the fluid supply and receiving connectors in the demated and mated configuration prior to the transfer of fluid. Subsequent to fluid transfer the liquid lines are purged with helium before disconnecting to prevent potential liquid spills. In demonstrating this approach in vacuum, the connectors should first be leak checked in the disconnected configuration with the chamber evacuated. After this check the chamber should be brought to one atmosphere and the connectors manually connected. The chamber should be evacuated and, in this configuration, the connector volumes isolated and pressurized with helium. Leakage can be determined by the pressure decay rate, as described in Section 2.2.3. After verification of the leak checks the fluid should be transferred as in the one atmosphere fluid transfer demonstrator.

To eliminate possible spills at disconnect, the connector and line should be purged before demating with helium. The residuals should be collected in a container outside the vacuum chamber. After this operation the chamber should be brought up to atmospheric pressure and the fluid lines manually disconnected and stowed. Any significant leakage that might occur during fluid transfer can be detected by the facility gas analyzer.

6.0 REFERENCES

1. "1978 Extruding and Molding Grades", The International Plastics Selector, Inc., Cordura Publications, Inc.

2. Machine Design, March 17, 1977, pp. 112-113.

3. Ugural, A. C., S. K. Fenster, "Advanced Strength and Applied Elasticity", Elsevier Science Publishing, 1987.

APPENDIX A

Certification Documentation for the Air Tank Spheres

CHICAGO FLOAT WORKS, INC.

ESTABLISHED 1915
230 SCOTT STREET
ELK GROVE VILLAGE, ILLINOIS 60007

TELEPHONE 439-6100 AREA CODE 312

Mr. John Carroll
SRS Technologies
990 Explorer Blvd. NW
Huntsville, AL 35806

Contract No.
Order No. 9507
Date of Shipment 10/25/88

Certification of Specifications

We hereby submit our affidavits certifying that the following items were manufactured to meet the designated specifications:

Pieces Shipped	Part No.	Material - Specifications	Description
2	N/A	14 Ga. Type 304 Stainless Steel	¼" I.P. Hex Drill Thru Retapped for Vacuum Seal Floats internally washed to remove all shop grease.

We hereby certify that one float was hydrostatically tested in oil for an internal air pressure of 350 PSIG. The ball was held to this air pressure for 25 minutes. It did not collapse, explode or leak.

by Sandra Westlund

on October 25, 19 88

Sandra Westlund

I certify that the material described above conforms to the above Specifications, including any waivers, revisions or amendments as noted above.

CHICAGO FLOAT WORKS, INC.

By Office Manager
Title

APPENDIX B

System Hardware Mechanical Drawings

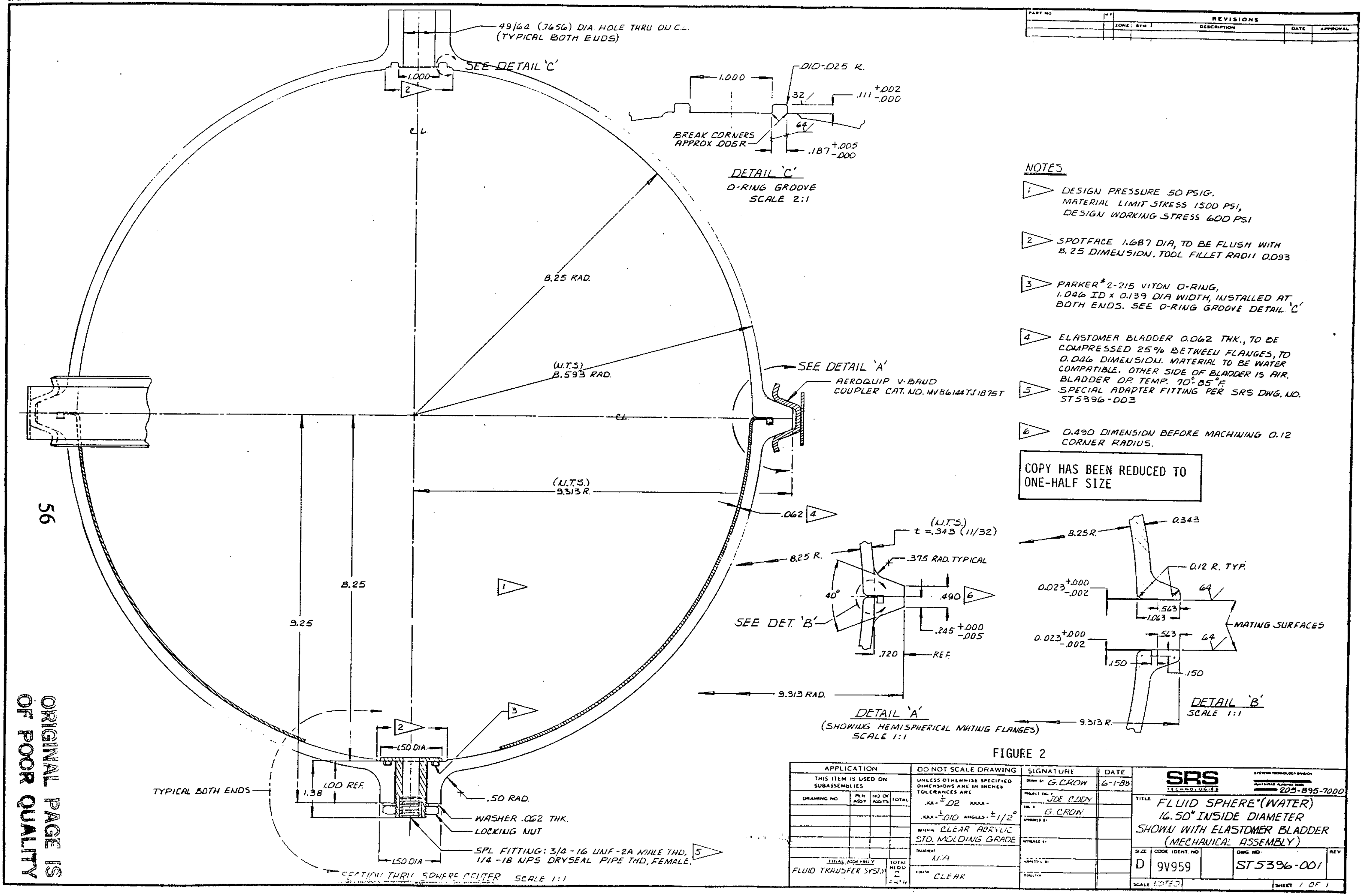


Figure B-1 Spherical Liquid Tank Conceptual Design

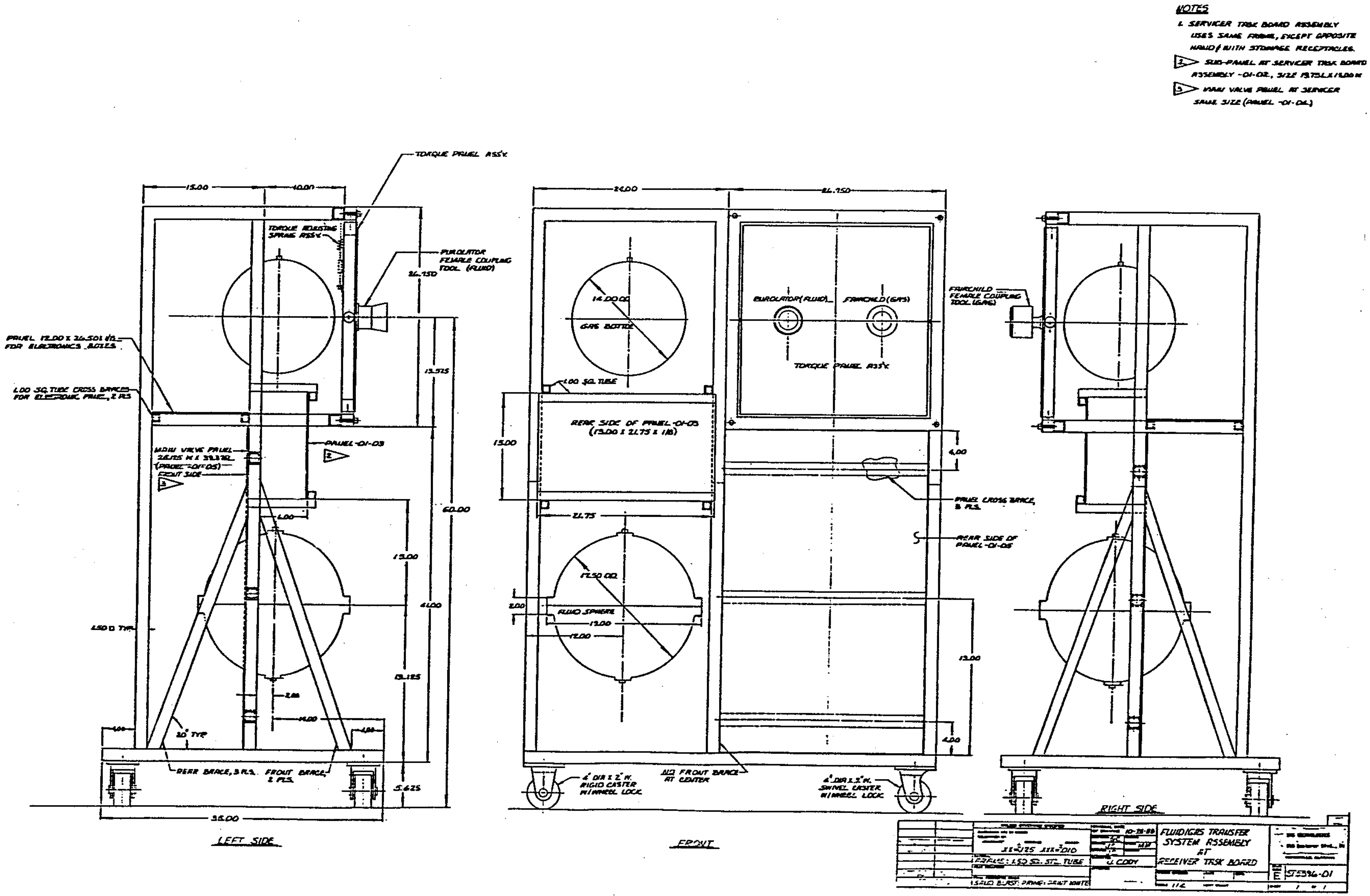


Figure B-2 Fluid Transfer System Framework Assembly

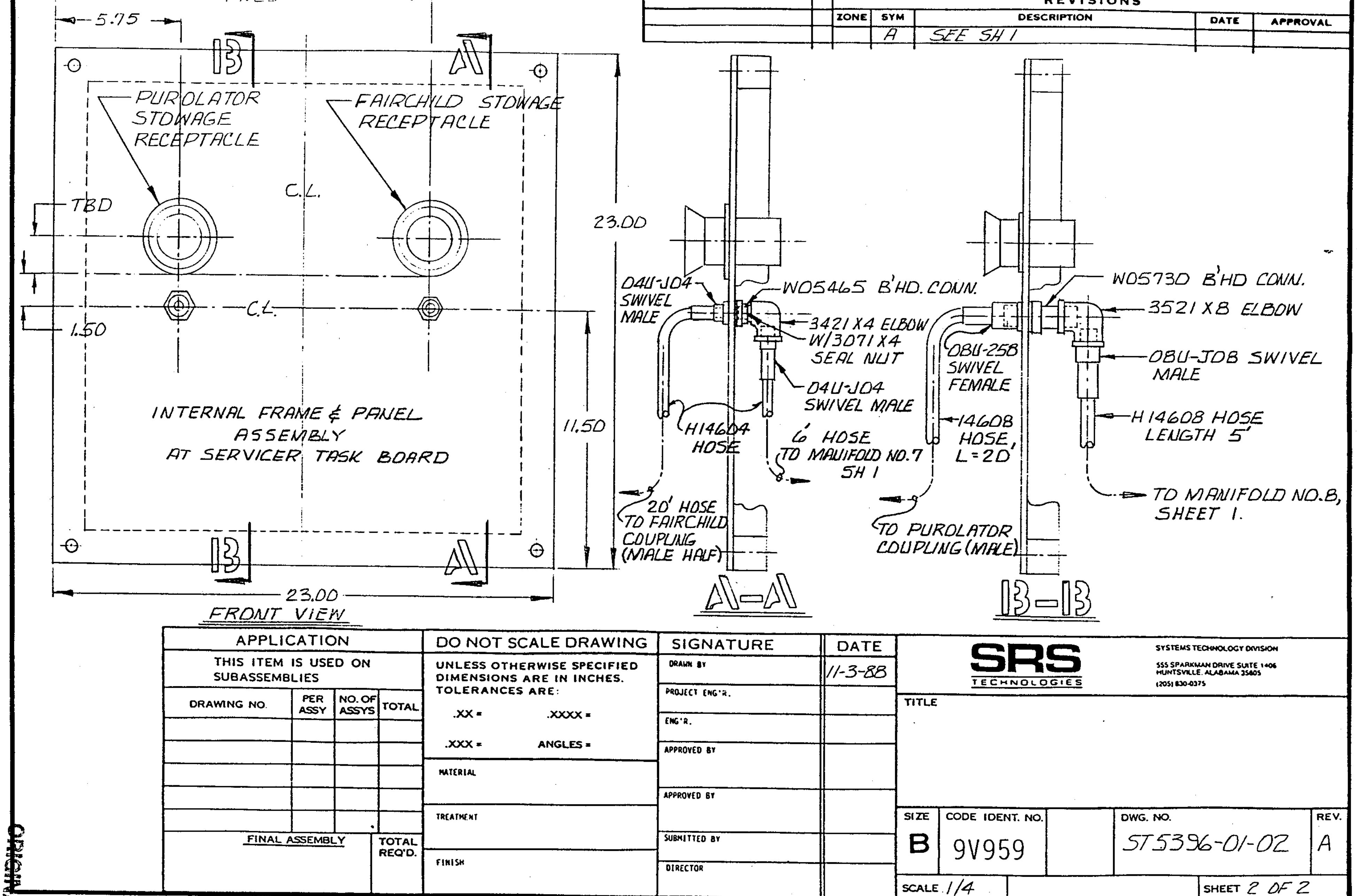


Figure B-3 Fluid/Gas Instrumented Task Panel Assembly at Servicer Task Board

ORIGINAL PAGE IS OF POOR QUALITY

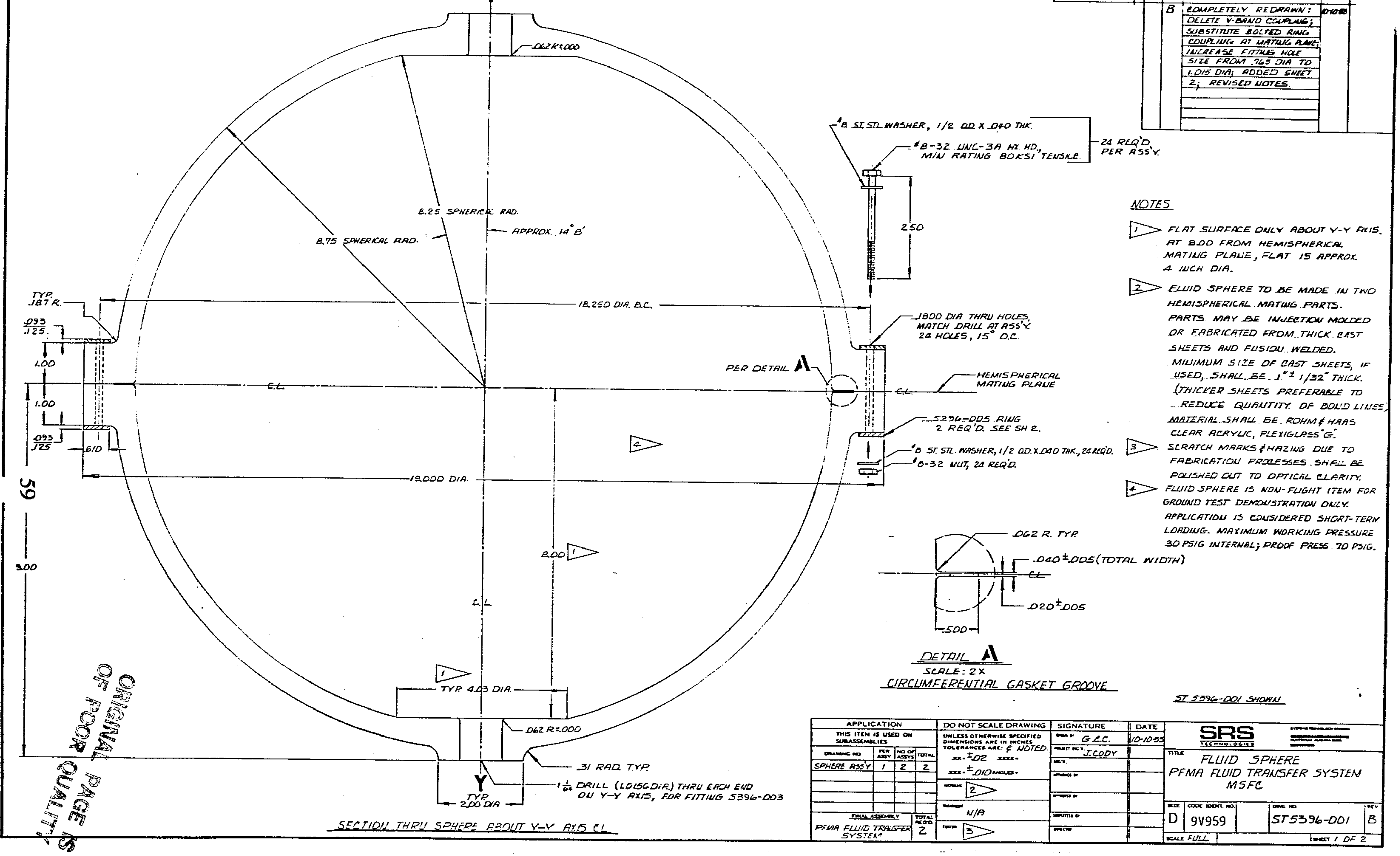


Figure B-4 Final Design of Liquid Spherical Tank of Fluid Transfer System

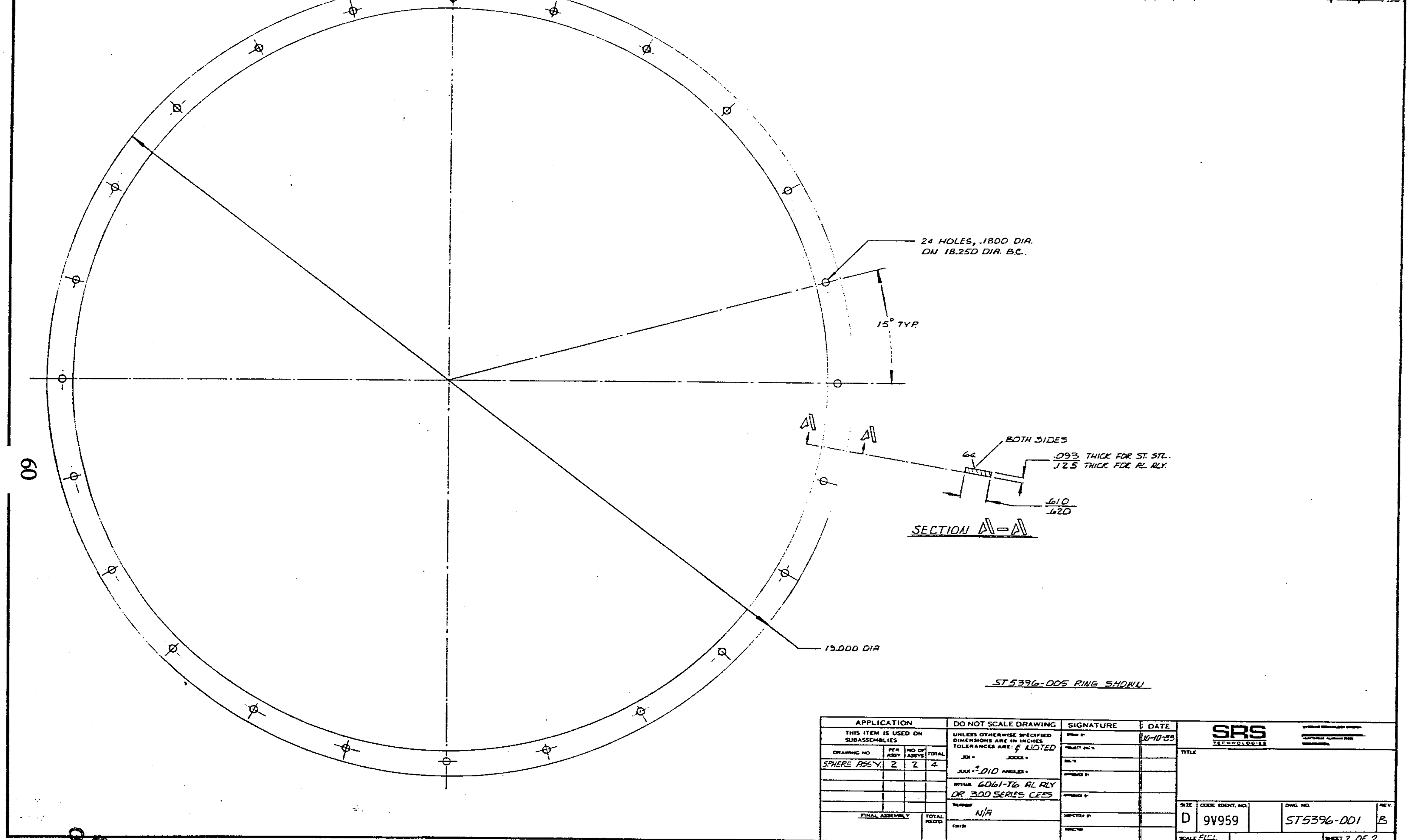


Figure B-4 (cont.) Final Design of Liquid Spherical Tank for Fluid Transfer System

(DO NOT INSTALL PRIOR TO
STRAIN GAUGE INSTALLATION)

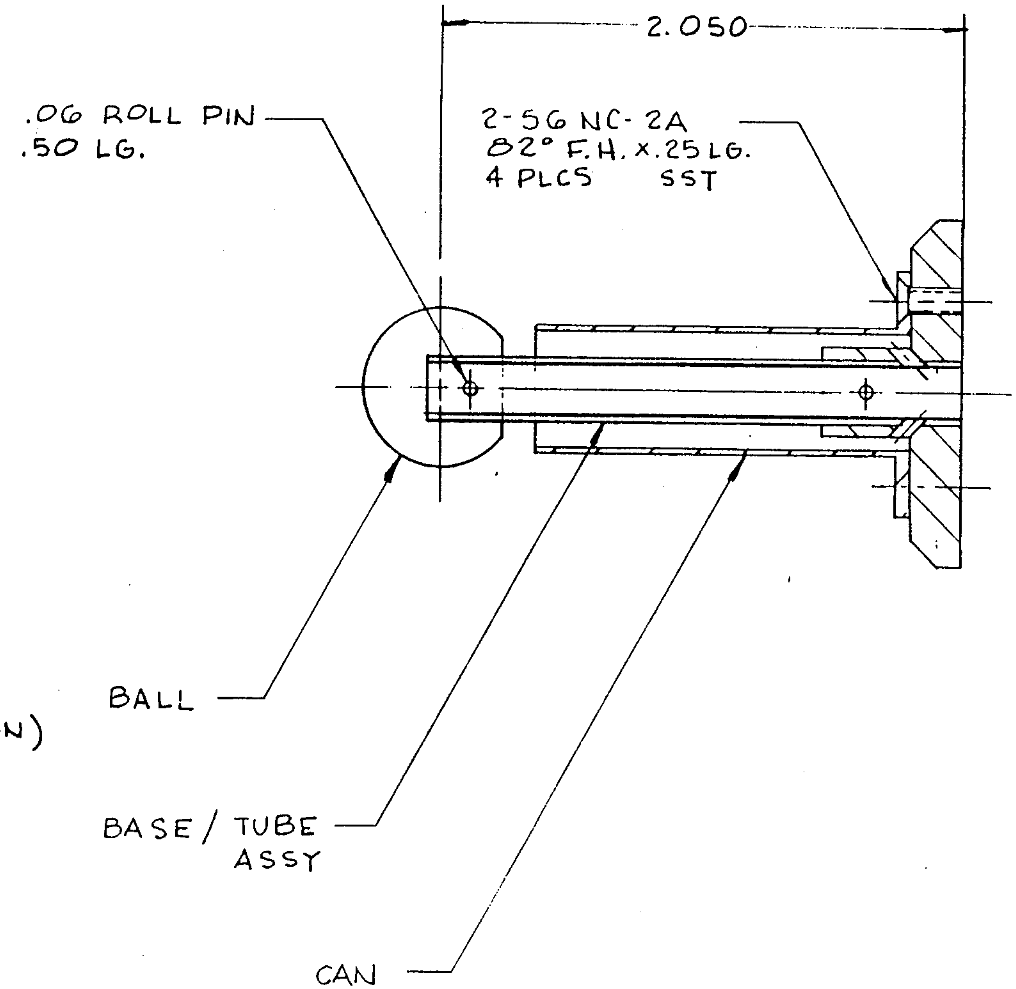


Figure B-5 Joystick Assembly

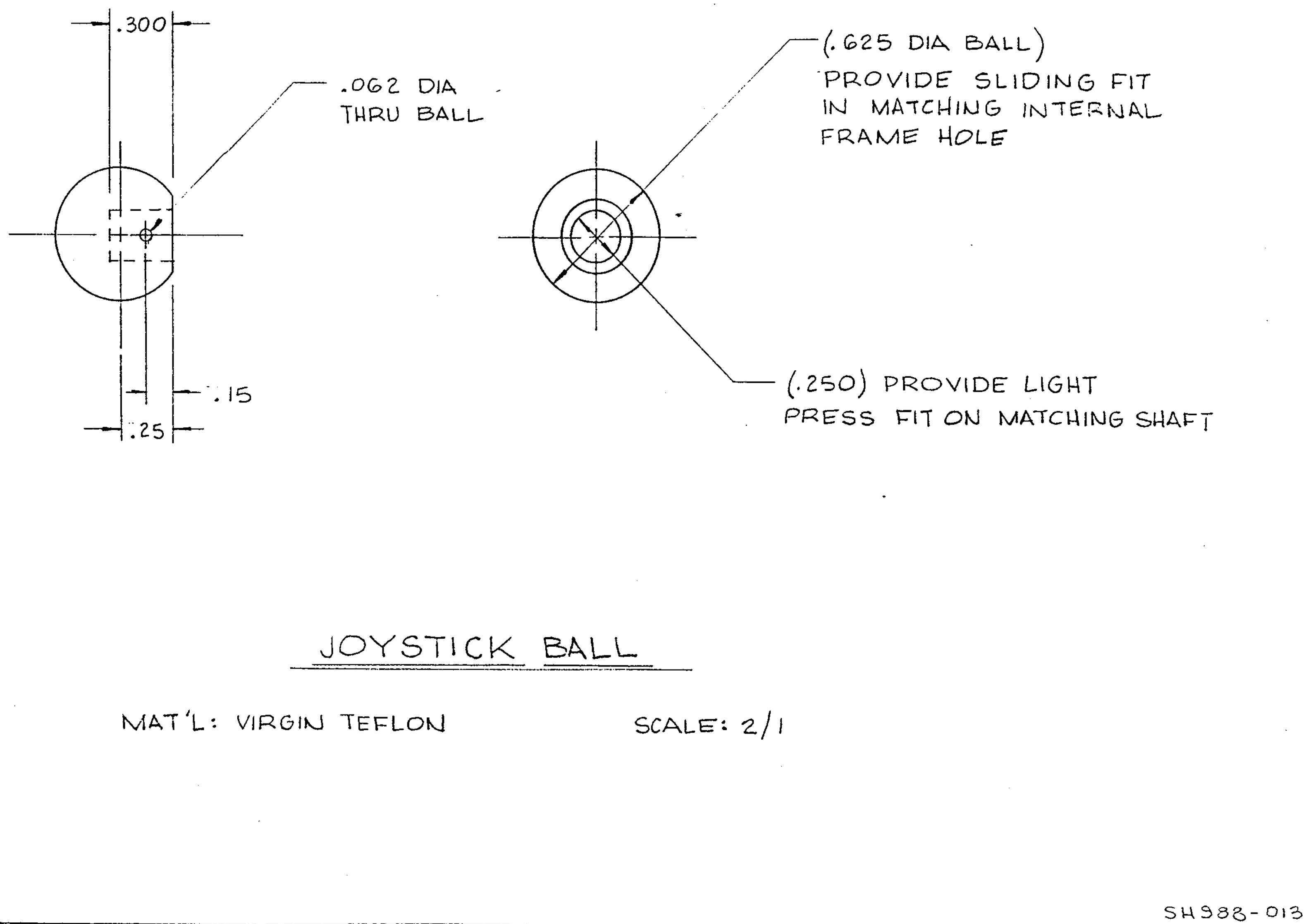


Figure B-6 Joystick Ball

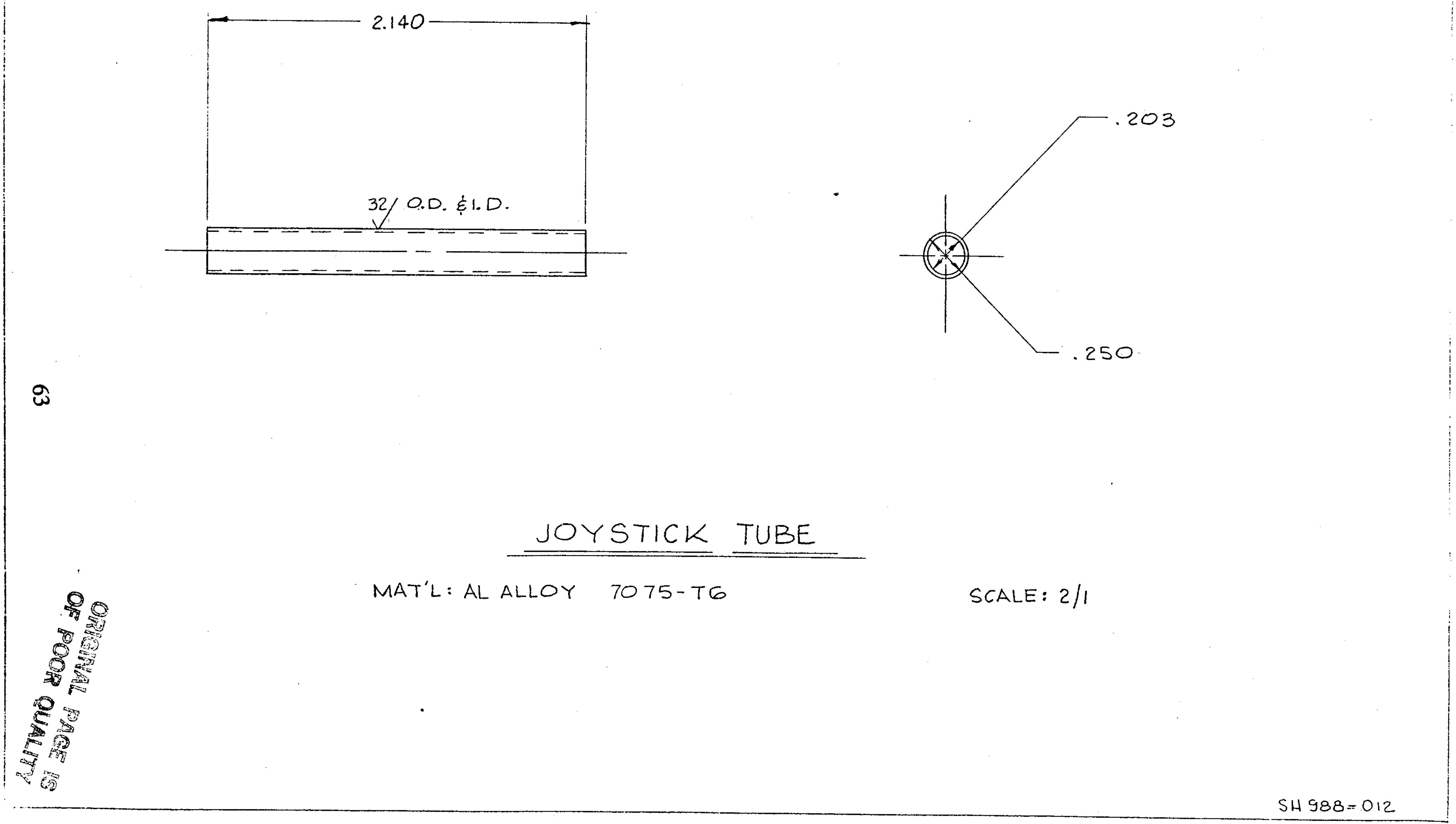


Figure B-7 Joystick Beam

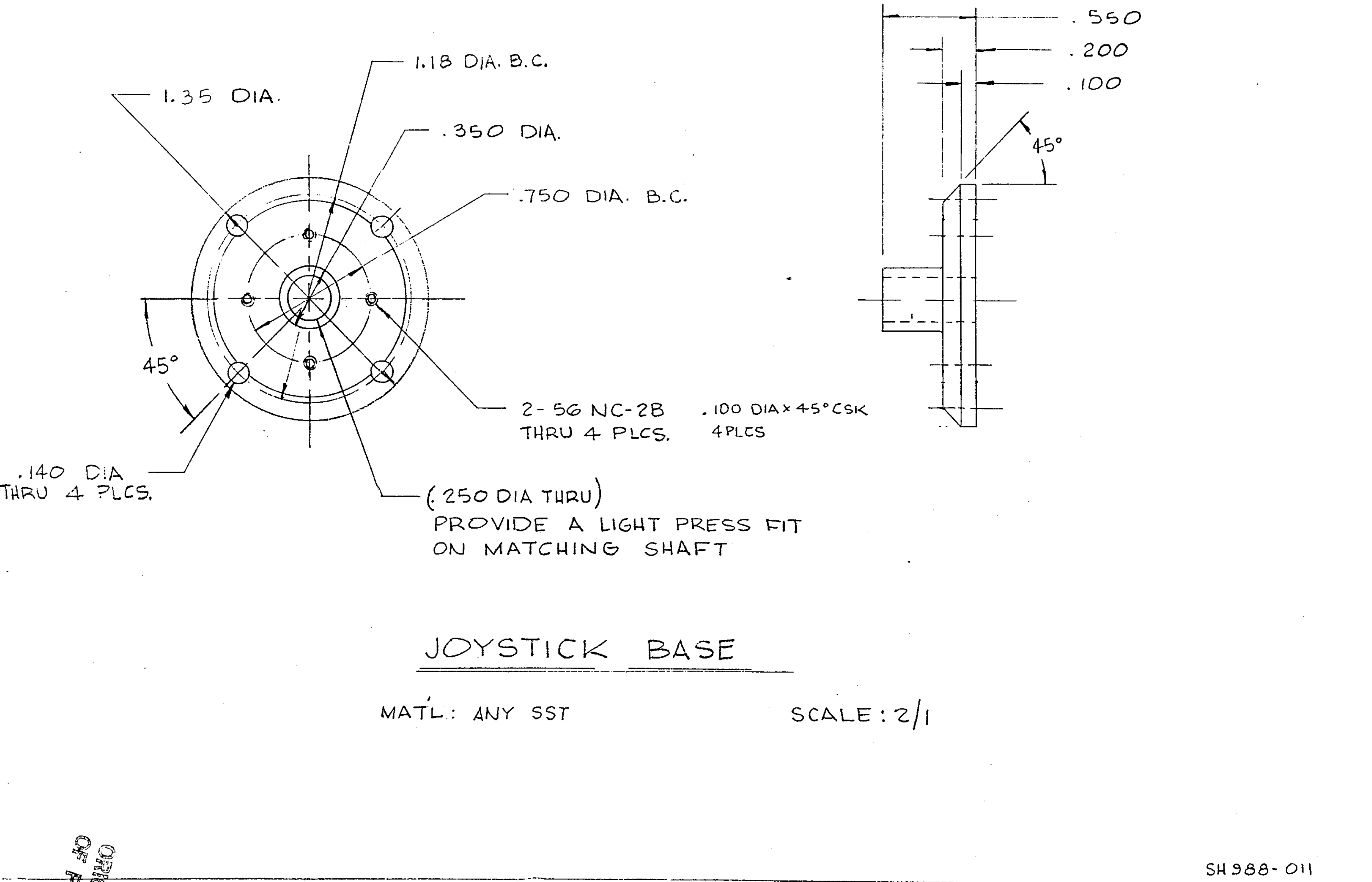


Figure B-8 Joystick Base

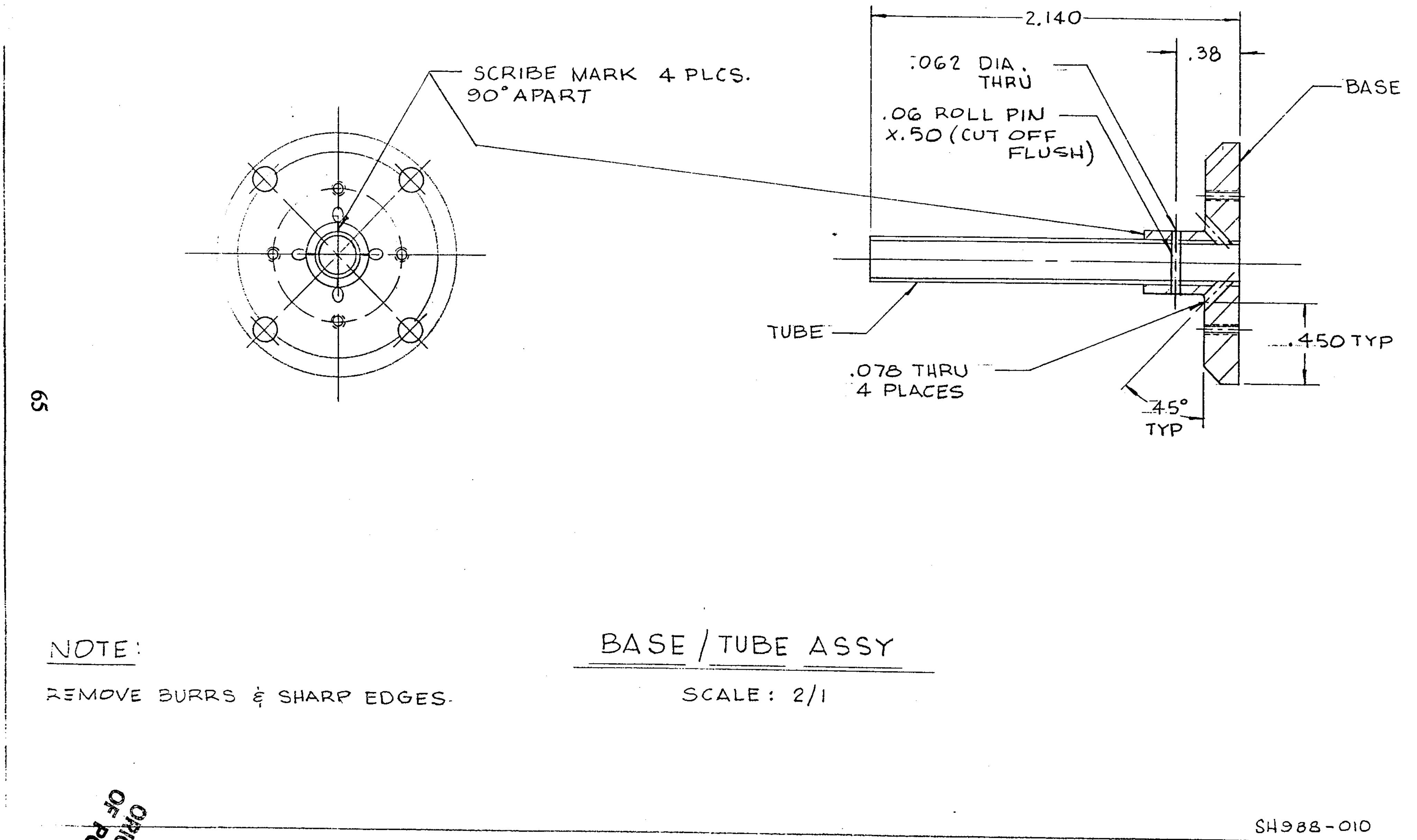


Figure B-9 Base/Tube Assembly

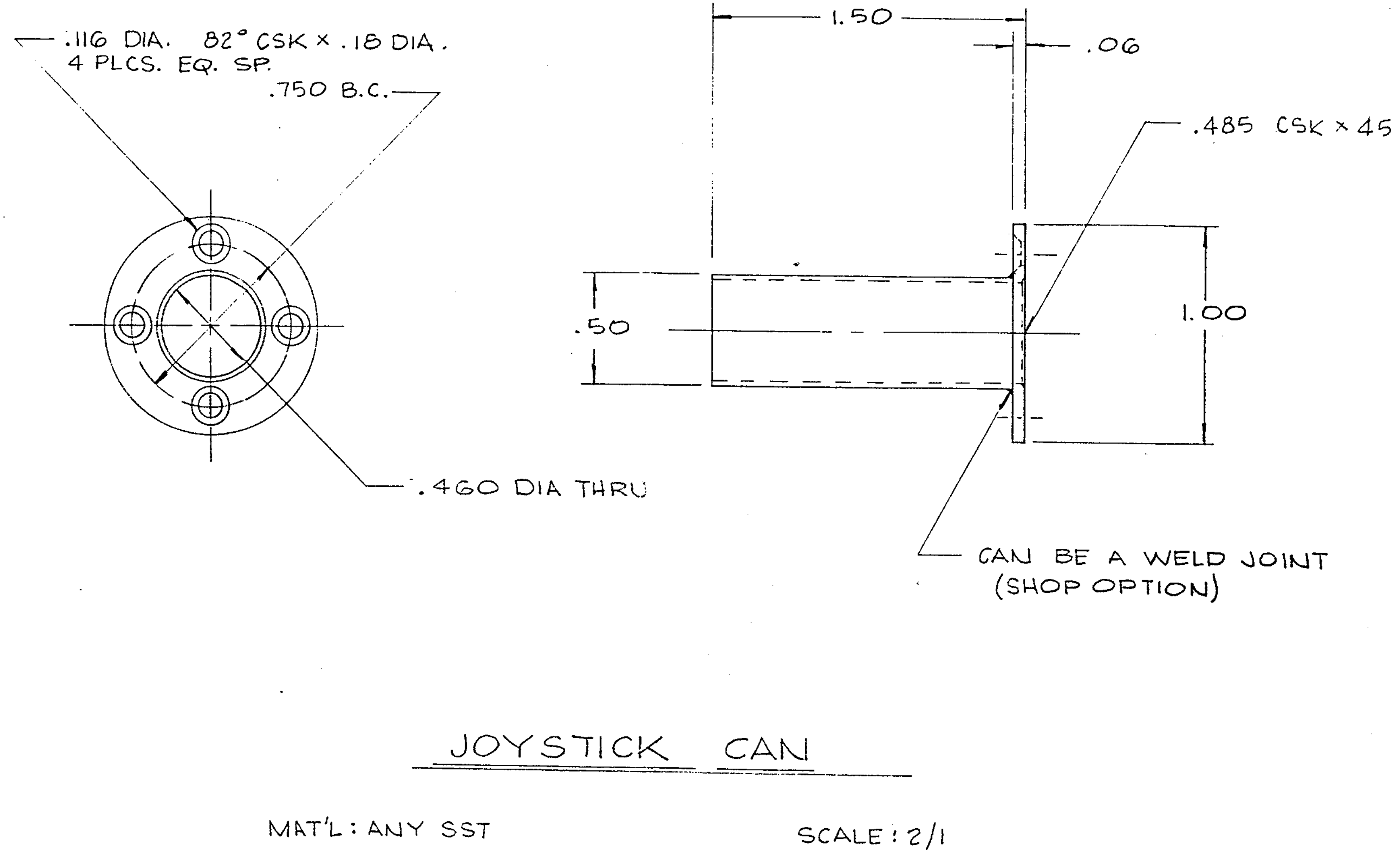


Figure B-10 Joystick Protection Canister

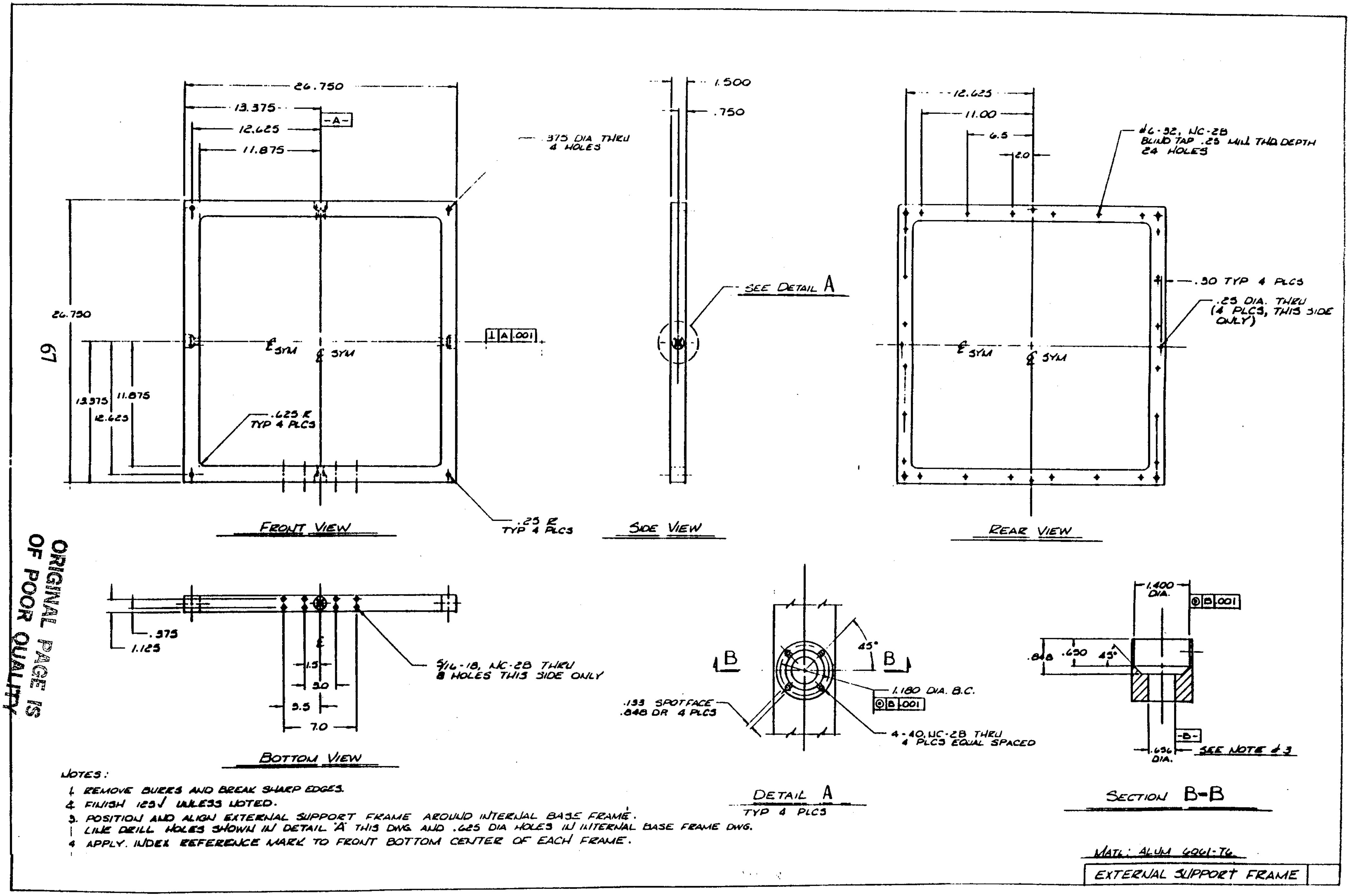


Figure B-11 External Support Frame for Force Measurement System

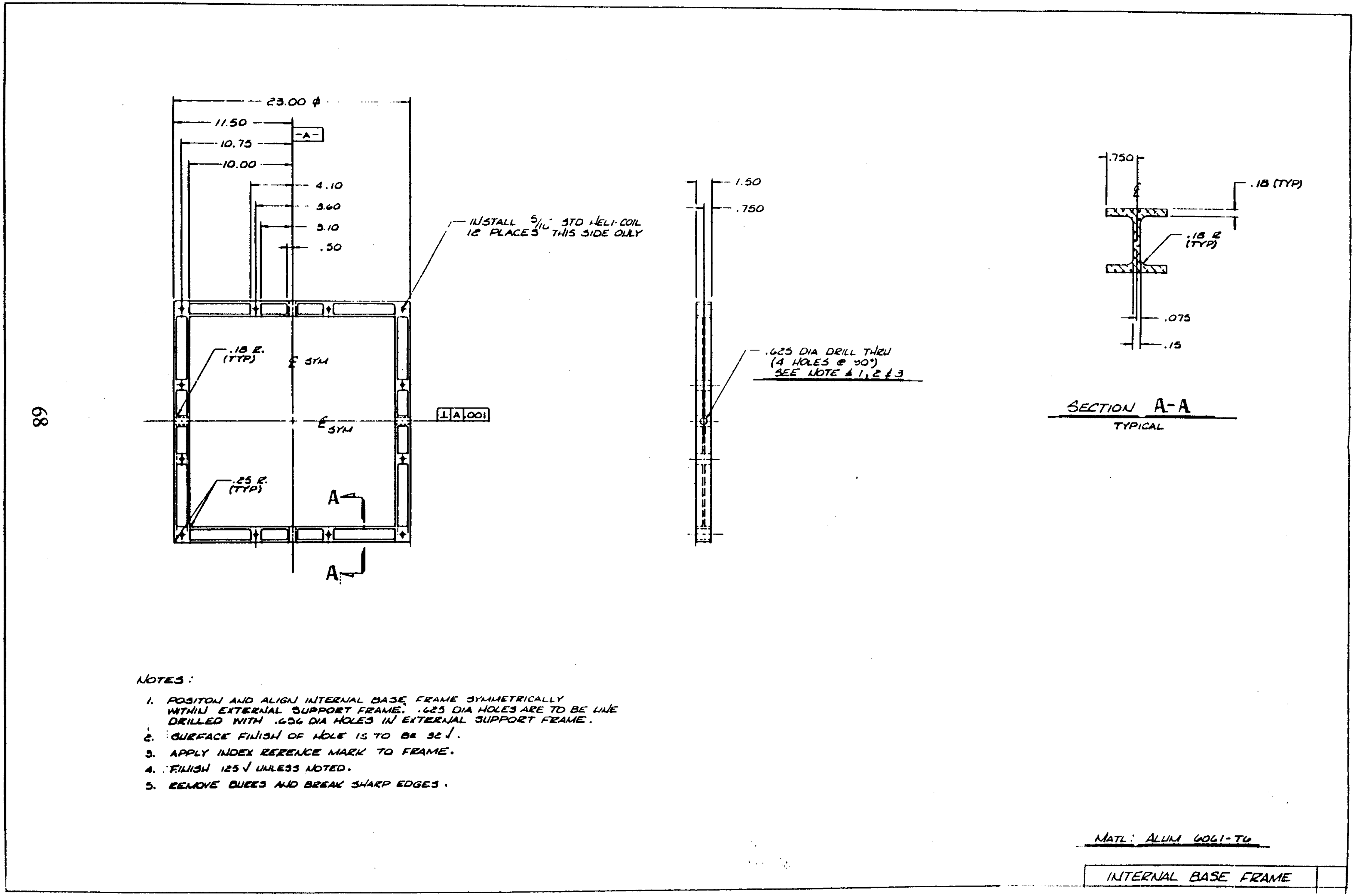
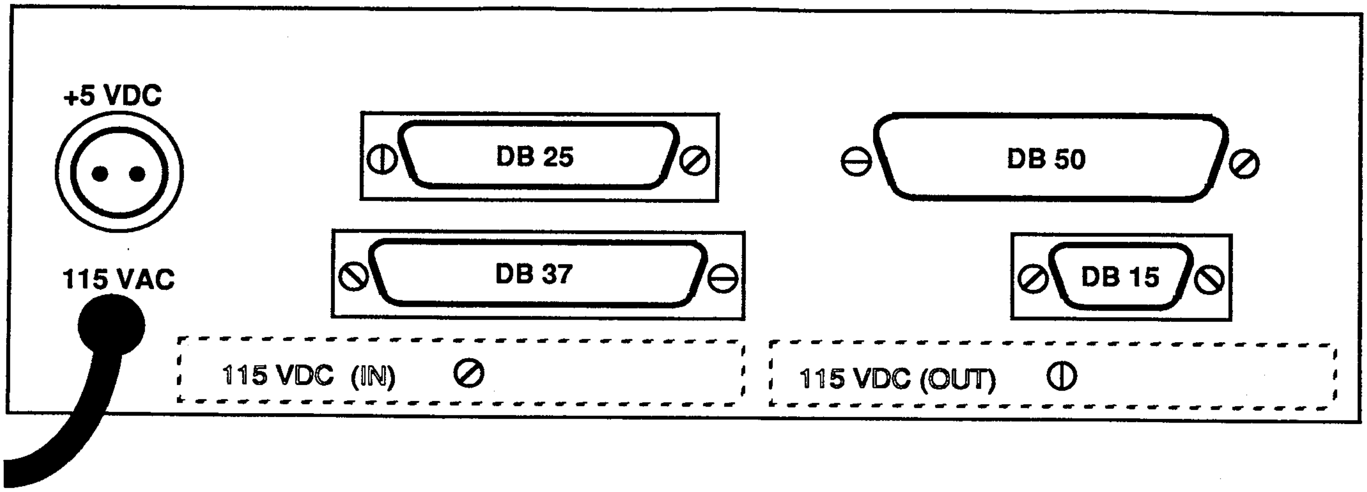


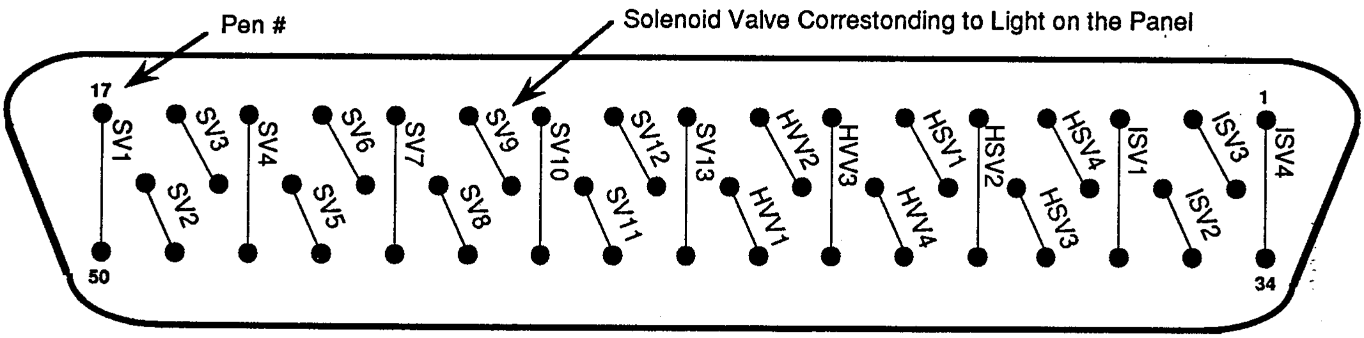
Figure B-12 Internal Frame for Force Measurement System

APPENDIX C

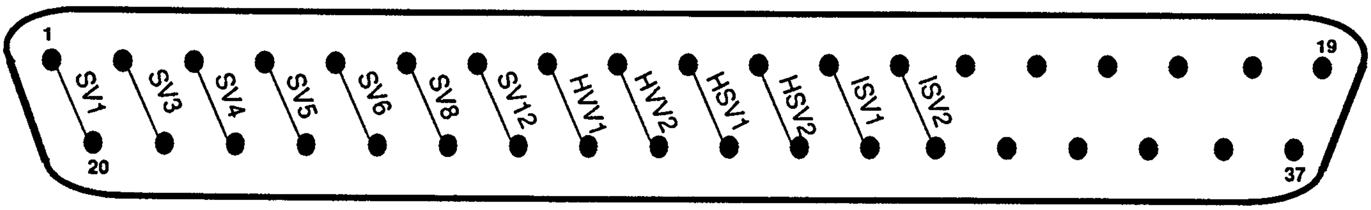
External Electrical Configuration for the Solenoid Valve Logic Controller



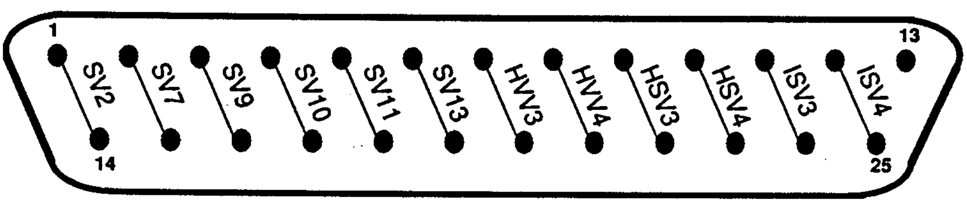
Connector for the Control Cable of the Solenoid Valve Operation Verification Panel (DB 50)



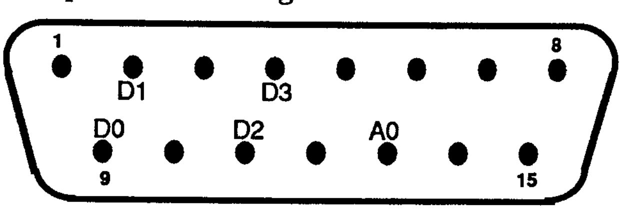
Connection for the Control Cable of the Supply Station's Solenoid Valves (DB 37)



Connection for the Control Cable of the Resupply Station's Solenoid Valves (DB 25)



Connection for the Control Cable from the Computer to the Logic Circuit



Logic Circuit Power Supply Connection

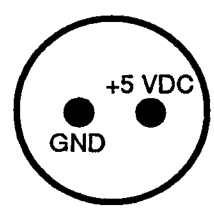


Figure C-1 Solenoid Valve Sequence Controller Connection Configurations